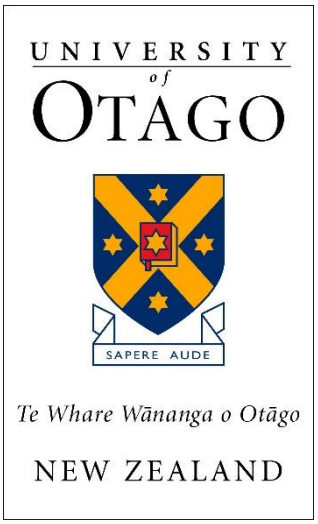
Evaluating the Long-term Success of Jewelled Gecko (*Naultinus gemmeus*) Translocations and Enclosure Suitability Within Orokonui Ecosanctuary

Ellen Richardson

A thesis
submitted to the University of Otago
in fulfilment of the requirements for the degree of
Master of Science
in Wildlife Management



University of Otago, Dunedin,
New Zealand
June 2021

A neonate basking on top of a female adult at the 2012 penned release site within Orokonui Ecosanctuary. Photography by Ellen Richardson, 2020.

Abstract

This thesis focused on evaluating the short- and long-term success of four separate translocations of jewelled gecko (*Naultinus gemmeus*) into and within Orokonui Ecosanctuary, Dunedin, New Zealand. The jewelled gecko is a diurnal, arboreal species of New Zealand green gecko, highly susceptible to predation, habitat loss and illegal poaching. Populations have been translocated to three sites within Orokonui ecosanctuary (from sites on the Otago Peninsula at high risk of illegal poaching) over three separate translocations that have used both penned and hard release methods. A fourth translocation of jewelled geckos (sourced from within the ecosanctuary) to Orokonui's new jewelled gecko enclosure began in December 2020. Understanding the short and long-term implications of translocation methods used, and assessing the suitability of the release site, is essential when refining best translocation practices for a species.

Firstly, I examined the stage of translocation success (based on the criteria of Miller *et al.*, 2014) and long-term dispersal of founders resighted at both the hard and penned jewelled gecko release sites within Orokonui Ecosanctuary. The penned release method was expected to reduce the dispersal of founder individuals long-term and therefore encourage future generations to establish at the release site. Thus, population growth (more individuals sighted than released) was predicted to be detected at the two penned release sites (released in 2009 and 2021) but not the hard release site (released in 2012). Between June 2020 and February 2021, 75 visual day surveys were conducted on sunny days when geckos were expected to be basking (equating to 392 person hours of searching). Suitable jewelled gecko habitat within a ~50 m radius of the release sites and habitat between sites were visually searched. Founders were identified through photo identification, and linear dispersal estimated. Eighty geckos were located throughout the ecosanctuary. The largest jewelled gecko population sighted was at the 2012 penned release site (40 individuals) and the smallest (10) at the 2012 hard release site. The release method used (penned versus hard release) did not have a detectable effect on the number of geckos found, the stage of translocation success reached or the distances

founder individuals moved, 8-11 years following release. Evidence of population growth at the 2012 hard release and penned sites was almost confirmed (with 2-3 more sightings needed) whereas the 2009 penned release site required 14 more sightings to satisfy the criteria for population growth in Miller *et al.* (2014).

Secondly, I examined the suitability of Orokonui Ecosanctuary's new jewelled gecko enclosure in terms of enabling and promoting natural behaviour. To do so, three key aspects of enclosure design were assessed: the thermal environment provided (and the thermal ecology it supports), the physical environment provided (location, habitat type, complexity and structure) and the effects of the spatial restrictions imposed (including the implications this has on home ranges and social interactions). Enclosure geckos were translocated and monitored as part of this study, between December 2020 and February 2021. The enclosure overall was predicted to be able to support ten jewelled geckos (the desired stocking density) without resulting in a loss of body condition over the 2-month study period. Thermal environments (that support natural basking behaviour) were expected to be similar between sites, however an adjustment period was predicted to be detected in gecko basking behaviour (frequency of full exposure during basking and skin temperatures reached, as geckos adjusted to their new environment and visitors circling the enclosure). All habitat within the enclosure was predicted to be used by enclosure geckos. Home ranges were predicted to be reduced as a result of the natural restrictions the enclosure imposes on gecko movements; this was expected to increase the number of interactions between geckos. Thermal environments available to geckos at the wider ecosanctuary and enclosure sites were measured using calibrated copper models, and body temperatures reached during basking were estimated with skin body temperatures captured with a thermal camera. Radiotracking was used to better understand the movements and home ranges of free-roaming geckos and information on the basking behaviour, habitat use and perch height of free-roaming and enclosure geckos was collected, and a body condition index estimated.

The enclosure's thermal environment was significantly cooler than those at the 2009 penned and 2012 hard release sites. However, all sites enabled geckos to reach their set point temperature range (the central 50% of temperatures jewelled geckos selected when under a thermal gradient), and natural basking behaviour was observed in enclosure geckos. While the enclosure restricts individual home ranges, no aggressive interactions were observed, and body condition significantly increased over the two-month study period. These results

suggest that stocking density (of eight geckos) was not an issue within the first two months following translocation. Free-roaming geckos used a wider range of habitat types than available to the enclosure geckos and free-roaming geckos occupied significantly higher perch heights than enclosure geckos. Enclosure geckos were observed using only two thirds of the suitable basking habitat available, with sightings clustered at two key points on the eastern and western sides of the enclosure and few observations made in the northern side and centre of the enclosure.

This research increases our understanding of the long-term effects penned and hard release methods have on the translocated population of jewelled geckos. There is a need however to further research the factors driving the success and failure of hard released green gecko populations to confidently determine the effect of penning green geckos on long-term establishment. This research also highlights that Orokonui Ecosanctuary's jewelled gecko enclosure is suitable short term. Age-related increases in home range size however, are predicted, which can lead to competition and territoriality among resident geckos. Therefore future research must focus on monitoring body condition and interactions between enclosure geckos to confirm the enclosure suitability long-term.

Acknowledgements

This research was conducted at Orokonui Ecosanctuary. I would therefore first like to thank Kati Huirapa Runaka ki Puketeraki and Te Rūnanga o Ōtākou , the Otago Natural History Trust and the Orokonui Knowledge Group for supporting this research and giving me the opportunity to study this beautiful species. I am incredibly grateful to the New Zealand Federation of Graduate Women for awarding me the Brenda Shore Award. This fully supported the purchase of Holohil transmitters, and the Canon camera and Tamron lens used throughout my research. Thank you to my supervisors Stephanie Godfrey, Alison Cree and Jo Monks for their abundance of guidance, advice, support and detailed comments on my manuscript drafts. The knowledge you shared and time and support you all gave, in particular when things weren't going to plan, was invaluable. Thank you to the staff at Orokonui Ecosanctuary, especially Elton and Kelly who have spent hours staring at bushes with me and supported me throughout my fieldwork, in particular when technology was failing me. In addition, thank you to those who gave their time to assist with visual searches (Orokonui staff, volunteers and friends). Thank you to Joel Knight and Nick Harker for distributing my survey and to all the participants who took the time to share their experiences with me. Additional individuals who gave their time to help me include Carey Knox, Stu Borland, Christian Chukwuka and Jo Virens. Thank you for your invaluable knowledge, advice and support.

Finally, thank you to my wonderful friends and family, your support always means the world to me. Individuals I would like to thank in particular include: my parents - I think about jumping on a plane to see you almost every day but the distance has never stopped the infinite support you, and Alfie give me. Anya, thank you for coming to the rescue and holding the ladder for me while I scrambled up trees; Myrene, thank you for always being someone I can talk to, and for your endless support throughout this journey. Rachael, Jolene, Yelah, Josie, Lucy, Amy, Stephen and everyone in the Wildlife Management gang, thank you for your constant support and friendship.

Table of Contents

List of Figures

List of Tables

Table A.1.1. The results of this green gecko enclosure design survey conducted as part of this thesis. In total, seven responses were collected (with information on 16 green gecko enclosures): four from professional (*n* = 4) and 12 from private collectors (*n* = 3, all private collectors had >1 green gecko enclosure). Enclosure sizes and stocking densities used for previous green gecko penned translocations and some authorised holders throughout New Zealand based on responses to a green gecko enclosure design survey distributed in December, 2020. A release pen refers to an outdoor penned area within which geckos were temporarily confined for a defined period of time prior to release into the wider area. Studies reporting these pen areas have been added to the table to provide further information on the size and density green geckos have been held at. *Biting was observed once and a daughter seen several times edging itself over the mother below the heat lamp.....105

CHAPTER 1

General Introduction

We are currently experiencing Earth's sixth mass extinction. This has been driving declines in global biodiversity and species to extinction for the past 500 years (Dirzo *et al.,* 2014), primarily due to overexploitation and agriculture (Maxwell *et al.,* 2016; Johnson *et al.,* 2017). New Zealand in particular, has suffered extensive loss of biodiversity and ecosystem integrity following the arrival of Polynesians in the 13th century (and the arrival of mammalian predators and extensive land use changes that followed; King, 1984; Towns and Daugherty, 1994; Gibbs, 2009). Despite more than a century of conservation efforts, invasive species, ecosystem change, pollution, overexploitation, accelerated climate change, limited knowledge and habitat fragmentation, continue to slow the recovery of New Zealand's threatened species (Hare *et al.,* 2019).

New Zealand is home to more than 110 endemic species of terrestrial reptiles (the tuatara, geckos and skinks), with at least 43 species of geckos, belonging to seven genera: *Tukutuku, Hoplodactylus. Mokopirirakau, Toropuku, Dactylocnemis, Woodworthia* and *Naultinus* (Chapple, 2016; Van Winkel *et al.,* 2018). Currently, 12 endemic gecko species are classified as "Threatened" and 15 species as "At Risk" by the New Zealand threat classification system (Hitchmough *et al.,* 2021). Predation and habitat loss pose the biggest threats to these species' survival in the wild (Hitchmough *et al.,* 2021). Other threats include poaching, invasive reptiles, disease and climate change (Nelson *et al.,* 2014). Habitat specialization, large body size, restricted geographic ranges and a diurnal, arboreal lifestyle, only exacerbate the risk of extinction (Tingley *et al.,* 2013). Conservation efforts to address such threats are ongoing (involving, in particular, large scale predator control and translocations to islands and mainland fenced ecosanctuaries with no or few introduced mammals). These efforts have been successful in boosting some species' abundances (Reardon *et al.,* 2012; Nelson *et al.,* 2019).

A fenced ecosanctuary is characterised by a predator-resistant fence surrounding an area >25 hectares, within which mammalian predators are eradicated (except for mice, which must be routinely suppressed; Innes *et al.,* 2019). In New Zealand, populations of native and endemic

species are often translocated to a fenced ecosanctuary. Such translocations enable the return of (often threatened) species, to the mainland of New Zealand and assist in their recovery (e.g., hihi, *Notiomystis cincta*, tuatara, *Sphenodon punctatus* and wētā; Watts *et al.,* 2011; Innes *et al.,* 2019), especially by offering protection during vulnerable life stages until individuals are fit to be returned to the wild (e.g., Operation Nest Egg; Germano *et al.,* 2018).

Use of Translocations for Conservation

A Translocation is defined as the accidental or intentional human-mediated movement of wild or captive living organisms from one area to another; such movements are becoming an increasingly used conservation tool for global biodiversity conservation (IUCN/SSC, 2013; Berger-Tal *et al.,* 2019). The type of translocation is determined by its purpose, which can be driven by welfare, research, political, commercial, recreational or conservation motivations (IUCN/SSC, 2013). Conservation translocations have a conservation benefit for the focal species and are often used to reduce the extinction risk of, in particular, small and fragmented populations of threatened and keystone species (Weeks *et al.,* 2011; IUCN/SSC, 2013; Gilbert and Soorae, 2017). This is achieved through either supplementing small wild populations (reinforcement) or re-establishing a population within (reintroduction) or outside its indigenous range (a conservation introduction, which can be categorised as either assisted colonisation or ecological replacement; IUCN/SSC, 2013).

To encourage the establishment of translocated populations, a range of release methods have been developed. These vary in the level of supplementation provided to ease the transition to the new area. A soft release involves the provision of supplementary food, water or shelter to reduce the risk of competition for food, starvation, exposure or predation following release. It is most valuable when the suitability of the area is not fully understood. A hard release, however, provides no assistance following the immediate release (Richardson *et al.,* 2015; Knox *et al.,* 2017). An additional method that does not always fall neatly into either of these categories is a penned translocation. Although a penned translocation can be combined with various degrees of supplementation, there has been some inconsistency in the use of the term, as a penned release with no supplementation has sometimes been considered as a soft release (Treglia, 2010; Tetzlaff *et al.,* 2019). To avoid confusion, I classify penning as its own release method, defined as penning a founder population within a defined area for a pre-determined period of time, before release to the wider area (following Knox and Monks, 2014).

The release method used can influence how successful a translocation is in terms of encouraging the founder population to establish at the release site. A commonly reported difficulty encountered during hard-release translocation programs is large initial dispersal of founder individuals (Berger-Tal *et al.,* 2019). This will have the largest influence on the translocation success of species with small home ranges, as high rates of initial dispersal will likely reduce the incidence of mating once established (Knox and Monks, 2014; Berger-Tal *et al.,* 2019). The penned-release strategy, however, can significantly reduce the dispersal of founders following release, probably because it encourages the formation of stable territories within the release site (e.g., New Zealand green geckos; Knox and Monks, 2014; Knox et al. 2017; Flynn-Plummer and Monks, 2021). A lack of effective monitoring (for cryptic species), suitable release habitat, funding, baseline knowledge of species' ecology and behaviour and public support, are additional factors that often hinder the success of conservation translocations (Berger-Tal *et al.,* 2019).

It must be noted that criteria used to confirm a successful translocation are inconsistent in the literature. This is because criteria are often shaped around the long-term goals of the translocation (from confirming a self-sustaining population to achieving long-term persistence at the release site) and the rate at which the focal species can achieve these goals (Miller *et al.,* 2014). For these reasons, Miller *et al.* (2014) created four-staged standardised criteria for assessing translocation success based on translocations of New Zealand herpetofauna. These stages take species' life history and time since release into account, which makes it easier to compare translocation success between species and to better identify causes of translocation failure (Miller *et al.,* 2014; Towns *et al.,* 2016).

Translocating Animals into Enclosures as a Conservation Tool

It is also common for ecosanctuaries to translocate rarely seen and threatened species into enclosures. The motivation can be to offer an additional experience to visitors and to enhance public knowledge and promote support for the protection, rehabilitation and reintroduction of that species (Ballantyne *et al.,* 2007; Ballantyne *et al.,* 2011; Cong *et al.,* 2014; Liordos *et al.,* 2017). Although the benefits are evident, enclosures are highly modified environments. The restrictions that enclosure design often impose (in terms of space, stimulation and climate) and regular exposure to visitors, in particular large and noisy crowds, hold the potential to disturb and stress captive animals.

The concept of stress in animals is widely used but there is a lack of consistency when it comes to its definition (Koolhaas *et al.,* 2011). In this thesis, the definition of "stress" offered by Koolhaas *et al.* (2011) is used. In their study, stress refers to an individual's state when in an unpredictable and uncontrollable situation (based on the individual's perception of control). This is triggered by a stressor (a stimulus that has the potential to be life threatening). The intensity and persistence of a stressor can dictate the degree to which the animal is affected, ranging from mild consequences (as an animal attempts to cope with the stressor) to posing a risk to the animal's survival (chronic stress; Koolhaas *et al.,* 2011; Beenher and Bergman, 2017).

Changes in behaviour (such as the adoption of antipredator aggression and avoidance or energy-saving behaviours) can be one of the first indications that an animal is under the influence of a stressor (Wingfield, 2006). Stereotypic behaviour (defined as abnormal, repetitive and functionless behavioural patterns) can develop; these are often considered to be a sign of stress and an indicator of poor animal welfare (Mason, 1991). Behavioural indicators of stress are often reflected in physiological measures of glucocorticoids (or GCs, primarily cortisol or corticosterone; Wingfield, 2013; Beenher and Bergman, 2017). An individual experiencing stress however, is not always able to be confirmed using these measurements (Van Eck *et al.,* 1996; Summers, 2002; Warwick *et al.,* 2013).

Behavioural Indicators of Stress in Captive Animals

Response to Visitors

Due to the spatial restrictions that enclosures impose, captive animals may be unable to escape or avoid stimuli that cause discomfort, such as visitors and noise. The development of stereotypic behaviour in response to visitors has been reported in many captive species of mammals, including increased vigilance behaviour and/or movement in response to increasing numbers of visitors for primates, wild cats and elephants (Quadros *et al.,* 2014). Similarly, increased resting behaviour in response to visitor presence has been reported for Indian leopards (*Panthera pardus fusca*). This behaviour was thought to be an attempt to get as far away from visitors as possible (Mallapur and Chellam, 2002). Visitor presence can also elicit increased aggression towards conspecifics, or huddling and avoidance behaviour (as observed in captive little penguins (*Eudyptula minor*), all of which were interpreted as signs of fear (Sherwen *et al.,* 2015). In contrast with the situation for mammals, there are few published attempts to measure behavioural responses to visitors in captive reptiles

(Burghardt, 2013). Consequently, reports on the short- and long-term impacts of exposure to visitors on captive reptiles, are limited to those on avoidance behaviour, such as diving from branches into substrate or water (Warwick, 1990).

Environmental Provisioning

Stereotypic behaviour can also result from boredom or a lack of stimulation (often triggered by insufficient space to explore and a lack of naturalistic and complex habitat). This is particularly applicable to large, mammals with complex social dynamics (Lucas and Stanyon, 2017). It often develops when a captive animal has been exposed to the same ecological problem, such as hunting for food or finding a mate, for a long period without any success. Stereotypic behaviour can also be the result of learned laziness, especially if resources are readily available and if hunting, foraging or problem solving are no longer necessary (Engberg *et al*., 1972; Kuppert, 2013).

For decades, providing enriched and stimulating components (such as branches and problem-solving puzzles) to a naturalistic environment has been prioritised for birds and mammals. However, reptiles have been proven to also show communication, problem solving, play and sociality traits, so as in mammals, environmental enrichment is integral in promoting natural behaviour and good welfare (Burghardt, 2013). For example, the provision of thermal (perching/basking structures), feeding (puzzle feeders), olfactory (scented blocks) and object (rubber dog toys) enrichments significantly improved the frequency of natural behavioural indicators of welfare in leopard geckos (Bashaw *et al.,* 2016). Replicating a species' natural habitat can also be an effective form of enrichment (Benn *et al.,* 2019). Stereotypic behaviour that can develop in reptiles includes hyperactivity, hypoactivity, aggression towards conspecifics, distancing behaviour and interaction with transparent boundaries (Doneley *et al.,* 2018). Such behaviour is more commonly seen in reptiles within enclosures that provide little to no natural habitat or interactive features for mental stimulation, and when husbandry routines are repetitive (Doneley *et al.,* 2018).

The absence of materials for nesting and foraging can also trigger behavioural indicators of stress in relevant species, with signs of boredom, increased fighting and distressed stereotypic behaviours seen in primates (Chamove *et al.,* 1982; Baker, 1997). Furthermore, poorly suited substrate type and enclosure materials can place stress on animals' joints and legs with evidence of foot problems in African elephants due to concrete flooring (Lucas and Stanyon,

2017), which often causes chronic arthritis (Clubb and Mason, 2002).

Limited Space

Insufficient space can have severe impacts on the physical and mental wellbeing of captive animals, triggering the development of stereotypic behaviour (e.g. in chimpanzees; Herrelko *et al.*, 2015), infant mortality (e.g. in carnivores, especially for species with large home ranges, wide-ranging lifestyles and daily travel distances; Mallapur and Chellam, 2002; Clubb and Mason, 2007), increased aggression towards conspecifics (e.g. male dama gazelle, *Nanger dama*, Cassinello and Pieters, 2000) and suppressed growth (e.g. sheep, Horton *et al.*, 1991). Captive environments also tend to place significant spatial constraints on reptiles. This often forces individuals to live at a higher population density than they would be exposed to in the wild. Although the impacts of this on the welfare of the captive animal are determined by the social organisation and territoriality of the species, overcrowding is common (Hawkins and Willemsen, 2004). In some extreme cases there may not be enough space for all individuals to occupy an adequate amount of space (with individuals climbing on top of one another to move; Warwick *et al.*, 2013).

In other cases, the enclosure may provide enough physical space but still prevent all individuals accessing a facility or resource at the same time (for example if not enough basking sites are provided for all individuals to bask at one time; Warwick *et al.*, 2013). If territorial (and in particular aggressive) conspecifics are housed together, aggression and fighting can occur, especially while territories and dominance hierarchies are established (as seen in juveniles of the lizard *Anolis aeneus*, Stamps and Krishnan, 1998). Enabling such behaviour, in particular in a captive setting where space to retreat or hide is limited, can put individuals at risk of severe injury or death (Hawkins and Willemsen, 2004). High-density captive populations can also result in reduced frequency of breeding as olfactory saturation can make it difficult for individuals to pick up on reproductive cues (Hawkins and Willemsen, 2004). Furthermore, enclosures that restrict the movement of reptiles and that do not accommodate behaviours such as diving and rapid movement, can cause physical injuries such as lesions on the snout, bone fractures and accidental collisions with enclosure walls (Warwick, 1990).

Climatic Suitability

A key concern for outdoor enclosures is the suitability of the natural climate, especially if sufficient shelter and/or heat sources are not provided (Morgan and Tromborg, 2007). Pacing and other abnormal behaviours can develop in response to unsuitable climate (e.g., Asian elephants, *Elephas maximus*, in temperatures < 9^{o}C; Rees, 2004) and the effects can be more severe when captive animals are exposed to extreme and unnatural temperatures (e.g., frost bite in rhesus macaques, Morgan and Tromborg, 2007). For animals held in indoor enclosures, artificial photoperiods, light quality, wavelength and brightness that do not address the species' preference and needs, can have detrimental effects. This is exacerbated by a captive environment where animals tend to have little to no control over the duration and nature of light they are exposed to (Morgan and Tromborg, 2007). The negative effects include alterations to sleep schedules, as well as increases in behavioural indicators of fear (e.g., red deer, *Cervus elaphus*, Pollard and Littlejohn, 1994), abnormal behaviour (e.g., in captive rhesus macaques, *Macaca mulatta*, O'Neill, 1989) and rates of aggression (e.g., male mice, genus *Mus*; van der Meer *et al.*, 2004).

Unlike birds and mammals, reptiles are ectothermic and therefore heavily depend on interacting with external thermal sources to regulate their body temperatures (Sunday *et al.*, 2014). In general, it is important that a reptile is able to reach the body temperatures (species specific) required for healthy physiological functioning. Otherwise, important functions such as metabolism, digestion, growth, reproduction and the immune system begin to fail. As a result, a reptile may become anorexic, immuno-compromised and more susceptible to disease (Wright and Cooper, 1981; Fleming *et al.*, 2003; Doneley *et al.*, 2018). Therefore, not only is the broader climate important, but the thermal regime is a specific aspect of reptile enclosure design that must be addressed. The natural or naturally replicated photoperiod and seasonal variations in temperature can also have enormous consequences for reproduction in captive reptiles (Warwick *et al.*, 2013; Doneley *et al.*, 2018). This is apparent for temperate reptiles in particular, whose reproductive activity is often linked to the seasons to assist in successful reproduction (Marion, 1982).

If indoor enclosures are not carefully designed and monitored, reptiles can reach their critical minimum or maximum temperatures. Once reached, reptiles can go into a cold narcosis state (severely reducing its ability to move and function properly; Weiser, 1973), heat stress, develop respiratory infections (Doneley *et al.*, 2018) and experience nutritional deficiencies

(Marais and Morgan, 1990; Burgess *et al.,* 2009). Unsuitable artificial heat sources (such as heat pads and light bulbs) also have the potential to burn individuals (Marais and Morgan, 1990; Gartrell *et al.,* 2019).

Study species: The jewelled gecko

Taxonomy and Appearance

New Zealand geckos are a distinct evolutionary group of lizards belonging to the family Diplodactylidae. Distinctive traits include residing in cold climates, viviparity (giving birth to live young), low annual reproductive output (one clutch of 1-2 neonates a year or in some species every 2-3 years) and great longevity (of more than 50 years in some wild species) (Chapple, 2016; van Winkel *et al.,* 2018). Most of New Zealand's geckos are nocturnal, primarily terrestrial, coloured brown, dull green or grey, and exhibit no sexual dimorphism. However, species in the *Naultinus* genus (the "green geckos" or moko-kākāriki) are strictly diurnal, arboreal and often brightly coloured, with sexual colouration seen in some males (Chapple, 2016; van Winkel *et al.,* 2018).

The jewelled gecko (*Naultinus gemmeus*; McCann, 1955) is a diurnal, arboreal lizard, endemic to the lower South Island of New Zealand, south of Canterbury (Chapple, 2016). Jewelled geckos have a maximum snout-vent length (SVL) of 80 mm and a total length of up to 160 mm (Whitaker *et al.,* 2002), with females reaching sexual maturity at an average SVL of 63 mm (Wilson and Cree, 2003; Cree and Hare, 2016a). Being sit-and-wait predators (Knox *et al.,* 2012), their primary defence tactic is to freeze and rely primarily on camouflage and refugia (Knox, 2011; Chapple, 2016). Individuals from the Otago Peninsula are well camouflaged against the vegetation, due to their bright green colouration with yellow and white stripes or diamonds, which are individually unique (Knox *et al.,* 2013). Jewelled geckos have also been observed to exhibit sexual dimorphism. Sexual dichromatism is seen in some sexually mature males (seen in Canterbury populations; Jewell, 2011; Chapple, 2016) and adult females tend to have larger snout-vent lengths (71.9 ± 0.5 mm; mean ± SE) than adult males (65.7 ± 1.4 mm; Wilson and Cree, 2003; Cree and Hare, 2016a). However, these morphological differences vary throughout their known geographic range (Jewell and McQueen, 2007).

Behaviour and Life-History

Jewelled geckos forage diurnally and remain inactive at night (Chapple, 2016). On warm sunny days, they are often observed basking on foliage to achieve warmer body temperatures. This basking behaviour changes throughout the day. Individuals are known to select higher body temperatures in the afternoon and night (seen when given a thermal gradient under lab conditions; Besson and Cree, 2011) and spot body temperatures reached during basking in the field ranging from 11-30^{o}C (Hare and Cree, 2016). They are known to have a critical thermal minimum temperature (the minimum temperature limit which if reached, animals lose the ability to right themselves) of 1.2^{o}C (Besson and Cree, 2011), and unusually, remain active year-round, continuing to bask in winter (Wilson and Cree, 2003; Chapple, 2016).

Pregnant females are more commonly observed basking than other geckos. With evidence of warmer maternal basking regimes shortening the gestation period for *Woodworthia* geckos (Cree and Hare, 2016b), this behaviour in jewelled geckos, is likely to address an increased requirement for warmth to assist with embryonic development (Knox, 2011). Further differences in behaviour are seen when analysing home ranges. While jewelled geckos will increase their range in response to patchy habitat, on average, males have significantly larger home ranges than females or juveniles (Schneyer, 2001). Schneyer (2001) suggested that this may be related to the distribution of mates in the wild (Rose, 1982) or a characteristic of the male foraging pattern (as seen in *Oligosoma grande*) (Eifler and Eifler, 1999). Alternatively, it may be evidence of territorial behaviour, which has been observed in wild and captive populations of jewelled geckos (C. Knox, *pers. obs;* Appendix 1). The home range of females is thought to be solely dependent on the resource availability within an area (Schneyer, 2001).

Jewelled geckos have a longevity of at least 12 years in the wild (Cree and Hare, 2016a) and >40 years in captivity (Knox *et al.,* 2019). They also have a low annual reproductive output. Females from the Otago Peninsula population are known to reach sexual maturity at three years old. Mating occurs between mid-winter and early spring (July and September) and females remain pregnant over summer for seven months before giving birth in mid-to-late-autumn to a maximum of two live young, annually (Wilson and Cree, 2003; Cree and Hare, 2016a). Neonates are therefore exposed to low temperatures when born e.g., as low as 11^{o}C by day and 7^{o}C at night on the Otago Peninsula (Cree, 1994; Wilson and Cree, 2003). However, populations at higher elevations (and therefore cooler climates) sometimes give birth later, in spring e.g., Banks Peninsula population (Cree and Hare, 2016a; Knox and Rate,

2018). Compared to other Southern Hemisphere geckos, the seven-month gestation period observed in jewelled geckos, is unusually long and appears to be unique to viviparous lizards in cool-temperate climates (Wilson and Cree, 2003).

Habitat

Jewelled geckos are known to inhabit forest, shrubland and vegetation up to 1100 m asl (Knox, 2014). Suitable habitat provides good camouflage, protection from predators, warm basking sites, refugia from extreme weather and fire, and sufficient food resources (including insects, fruit and nectar from native plants; Jewell and McQueen, 2007; Knox, 2011). While these geckos have been observed on 21 different plant species and on the ground (Knox, 2011), primary habitat for all green geckos includes dense divaricating shrubs such as *Coprosma* spp. (in particular *C. propinqua*, Salmon, 2002; Knox, 2011), dense kānuka (*Kunzea* spp.), mānuka (*Leptospermum scoparium*), tōtara (*Podicarpus* spp.) and large tussock grasses (Monks *et al.*, 2017). All of these are thought to provide important cover and protection from predators as well as fruit and insects (Schneyer, 2001; Jewell and McQueen, 2007; Knox, 2011; Knox *et al.*, 2012). Kānuka however, may not provide enough thermal refugia in the winter months to sustain a high population density (Knox *et al.*, 2012). In such habitats, ground cover (large tussocks, rank grass, ferns, low shrubs and rock outcrops) surrounding shrubland, can be essential as it provides refugia from hard frosts and extreme heat (Knox, 2011; Monks *et al.*, 2017), as well as protection from predators when moving between habitat patches (Jewell and McQueen, 2007).

Introduced plants such as gorse (*Ulex europaeus*), macrocarpa (*Cupressus macropcarpa*) and pine (*Pinus radiata*) can provide important habitat too, especially in areas where native plants are absent (Cree, 2003, Knox 2011). Evidence of populations persisting following fires (C. Knox, *pers. comm.*) and habitat modification suggests that jewelled geckos have the ability to adjust to a certain level of habitat change (Knox, 2011).

Threats and Current Distribution

Predation by introduced mammalian predators, in particular ship rats (*Rattus rattus*), mice (*Mus musculus*) and mustelids (Mustelidae), is a significant threat to the persistence and survival of wild populations of jewelled geckos (Towns and Daugherty, 1994). It is thought that avian predators are likely to pose a threat too (in particular kingfishers, *Halcyon sancta vagans*); however, evidence of avian predation on jewelled geckos has yet to be recorded

(Schneyer, 2001, Knox, 2011). While populations do persist in the presence of mammalian predators, population densities are severely reduced (Knox, 2011; Chapple, 2016; Knox *et al.*, 2017). Populations are most at risk when rank grasses are seeding, which increases the rodent, cat and mustelid populations (Wilson and Lee, 2010; Knox *et al.*, 2012). Ship rats may also compete with jewelled geckos for food, as a primary component of their diet is the berries of *Coprosma* species (Sweetapple and Nugent, 2007). The impact of this competition however, is poorly understood (Knox *et al.*, 2012).

Historically, fires and agricultural practices following human colonisation decimated areas of dense woody vegetation, especially throughout Otago (Jewell and McQueen, 2007). Today, only fragments of suitable habitat remain. Grazers and browsers (such as sheep, (*Ovis aries*), cattle (*Bos taurus*), European rabbits (*Oryctolagus cuniculus*), hares (*Lepus europaeus*) and brush tailed possums (*Trichosurus vulpecula*)) can contribute heavily towards the removal of essential habitat and ground cover that may be used as refuge (Knox, 2011). The resulting habitat fragmentation appears to reduce population densities (Knox, 2011). These patches of habitat can then drive geckos to increase their daily movements to locate sufficient food resources, which may expose them to increased rates of predation, especially if there is little to no ground cover (Schneyer, 2001; Jewell and McQueen, 2007). Shading of suitable habitat by other vegetation e.g., macrocarpa, gorse and broom, can further reduce available habitat (Knox, 2011). Illegal poaching is an additional threat, with 16 geckos smuggled from a population on the Otago Peninsula in 2010 (Knox, 2011).

It is believed that jewelled geckos were once widespread throughout Otago, Canterbury and Codfish Island. However, extensive modification and removal of essential habitat and predation by introduced mammals following human settlement, has left populations patchily distributed, with populations in Central Otago predicted to have gone extinct (Jewell and McQueen, 2007, Knox, 2011). Jewelled geckos are currently found naturally only in the southeast of the South Island, on Banks Peninsula, South Canterbury, the Mackenzie Country, northwest Otago, the Waianakarua area, Lammermoor range and on the Otago Peninsula (Knox and Rate, 2018; Knox, 2019).

Conservation Management

Jewelled geckos are ranked as ‘At Risk – Declining’ using the New Zealand Threat Classification System (Hitchmough *et al.*, 2021). This classification recognises that the

species occupies a total area of >10,000 ha (100 km^2); however, this area of occupancy is predicted to have declined by 10-70% by 2025 (Hitchmough *et al.*, 2021). Conservation management for the Otago Peninsula population has focused primarily on enhancing the suitable habitat available through the re-introduction of stock to manage rodent densities, predator control and planting of native, divaricating shrubs (Knox, 2011). Knox (2011) recommended the establishment of native forest and shrubland, with a focus on planting kānuka and divaricating shrubs as key priorities for conservation. Evidence of jewelled geckos reinvading regenerated sites suggests such efforts support the re-establishment of jewelled gecko populations (Jewell and McQueen, 2007). In addition, numerous translocations of *Naultinus* spp., (including jewelled geckos) to fenced ecosanctuaries have taken place throughout New Zealand. Such translocations have enabled the movement of geckos from areas at high risk of illegal poaching, to low risk and predator free environments (excluding mice) (Sherley *et al.*, 2010; McClure, 2011; Knox and Monks, 2014).

Jewelled Gecko Management at Orokonui Ecosanctuary

Orokonui Ecosanctuary (ranging from ~40 m to ~360 m asl) is located in Waitati, c. 20 km north of Dunedin. A predator-resistant fence encloses 307 hectares of primarily native, kānuka-dominated forest, shrubland and rank grass, free of introduced mammalian predators. Eradicating mice from the ecosanctuary remains a challenge. Instead, numbers are suppressed to a low abundance through annual poison operations and routine trapping, with the aim to reduce the mice to a tracking tunnel rate of <5 % (*pers. comm.* Elton Smith, conservation manager at Orokonui Ecosanctuary). The ecosanctuary's mission is to create a refuge, free of mammalian predators, for New Zealand's endemic and native species, and to provide the public with opportunities to encounter and connect with these species (Orokonui Ecosanctuary, 2021). In keeping with this mission, jewelled geckos have been introduced to the ecosanctuary over three separate translocations, in 2009 (penned release) and 2012 (penned and hard releases; Knox and Monks, 2014; Knox and Rate, 2018; Table 2.1).

Study Rationale

Assessing the success of a conservation translocation is an essential part of the translocation process. This knowledge allows the consequences of any challenges faced to be determined and this learning process can be used to better inform future translocations. According to the standardised criteria of translocation success recommended by Miller et al. (2014), none of

the 13 green gecko translocations conducted in New Zealand can yet be considered successful to the point where population growth has been achieved or a viable population established (stages 3 and 4). This is likely due to the 'slow' life history of green geckos and the effort required to monitor these cryptic species long-term. My study takes the opportunity to survey the jewelled gecko release sites within Orokonui Ecosanctuary, and the connecting habitat to assess the stage of translocation success 8-11 years post-translocation.

In addition, Orokonui Ecosanctuary recently built a viewing and captive breeding enclosure for jewelled geckos (in which it is anticipated that breeding will eventually take place). The enclosure was stocked between December 2020 and March 2021 and Orokonui staff expect it to support ten jewelled geckos (sourced from the wider ecosanctuary) and any enclosure born neonates in the future (which will be translocated out of the enclosure to the wider ecosanctuary). There are several green-gecko populations in captivity throughout New Zealand (Appendix 1). To my knowledge, this is the first outdoor, open-top, and naturalistic green-gecko enclosure, and is intended to not require any form of supplementation. Orokonui's enclosure therefore aims to find that balance between offering entertainment and education, while also successfully creating an enclosure that can support a healthy, small population of *Naultinus* geckos while promoting natural behaviours. Replication of such an enclosure is likely to be a popular management option for *Naultinus* geckos throughout New Zealand, in particular to improve advocacy opportunities for the species and to offer an additional experience to visitors. This study therefore took the opportunity to assess the suitability of this enclosure, as its success could have novel consequences for future management of *Naultinus* geckos in ecosanctuaries and zoos throughout New Zealand.

The design of this enclosure replicates the natural habitat used by jewelled geckos, and there are several captive groups of green geckos throughout New Zealand (Table A.1.1 in Appendix 1). Therefore, a successful initial translocation and long-term survival of 10 jewelled geckos (and enclosure-born neonates for a period of time) in the enclosure, may be expected. However, the enclosure environment is very different to what the geckos will be familiar with (in the wider ecosanctuary). As the enclosure is located on the grassland area, a key difference is the surrounding environment. Not only may the enclosure be more exposed to abiotic factors, but members of the public will be able to view the geckos in the enclosure up close (approximately 1 m from the edge of enclosure vegetation), between 0930 and 1630 five days a week.

In addition, the size of the enclosure is 50m^2. Jewelled geckos are known to occupy a mean home range size (± SE) of 31.1m^2 ± 7.5m^2 (measured from resident adult geckos in the Otago Peninsula population; Knox *et al.*, 2017). Furthermore, jewelled gecko home range sizes can be even larger for male adults (42.7m^2 ± 30.2m^2 compared to females: 24.9m^2 ± 11.9m^2 in the Otago Peninsula population; Schneyer, 2001). With the initial stocking density of 10 geckos, the enclosure will provide 5 m^2 per gecko. With the home range sizes reported above, and territorial behaviour observed in wild and captive jewelled geckos (Knox, 2011; *pers. comm.*, Joel Knight, Reptile Keeper at Wellington Zoo; Appendix 1), the enclosure size is expected to force the inhabitants to encounter a larger density of geckos they would naturally encounter and potentially restrict home range size.

A key concern is that the sudden and potentially high exposure to visitors may disturb the enclosure geckos and trigger behavioural changes (in particular the time they spend on essential activities like basking and foraging). The restrictions on movements and close proximity to conspecifics imposed by the enclosure size, may increase the number of aggressive interactions occurring, especially as new territories are established. In addition, the location of the enclosure (surrounded by open grassland rather than dense, *Coprosma* shrubs) and habitat structure (of a shorter and sparser structure than the vegetation that dominates the gecko's source location) may provide an unsuitable thermal environment with fewer basking opportunities. Important functions such as metabolism, digestion, growth and reproduction begin to fail if an ectothermic species is inhabiting an unsuitable thermal environment (Wright and Cooper, 1981; Fleming *et al.*, 2003; Doneley *et al.*, 2018).

It is therefore important to understand if any features of the new enclosure are triggering changes in behaviour budgets, body condition index (a measure of energy reserves available; Bonnet and Naulleau, 1994), increased risk of injury through aggressive interactions, or otherwise causing stress to individuals. Such changes can reduce the survival and reproductive rate of lizards (Tokarz and Summers, 2011). In addition, monitoring and enhancing the survival and reproductive rate of all species within Orokonui is of high priority for the ecosanctuary and will be essential for the success of the gecko enclosure. Physiological measures of stress were not undertaken during this study; therefore, I infer whether geckos are stressed through behavioural observations and measures of body condition.

Study Aims

The first aim of this thesis (addressed in Chapter 1) was to conduct the first full survey of Orokonui Ecosanctuary's translocated population. Surveys were focused around each of the three release sites and the connecting suitable habitat, to determine the stage of translocation success reached at each site, 8-11 years post-translocation (using Miller *et al.* 2014 criteria). This will test the prediction that Stage 3 of the Miller *et al.* (2014) criteria for translocation success (where more individuals are sighted than the propagule size) will be close to or have been reached at the two penned release sites. This prediction was based on the hypothesis that penning jewelled geckos reduces dispersal long-term as well as short-term (as reported in Knox and Monks, 2014). The effect of release method used (penned versus hard) on long-term dispersal of founder individuals was also of interest, to test this hypothesis.

The second aim (addressed in Chapter 2) was to confirm the suitability of Orokonui Ecosanctuary's jewelled gecko enclosure. To do so, the thermal environments available, basking behaviour, interaction rate and frequency, movements, habitat use and body condition index of enclosure and free-roaming geckos, were measured and compared. I predicted that enclosure gecko home ranges would be smaller than those of free-roaming geckos and that the number of interactions (social and aggressive) would be greater in the enclosure due to the natural restriction the enclosure imposes. It was also predicted that all developed divaricating shrubs within the enclosure would be used for basking and that the thermal environment present within the enclosure would reflect those at the three original release sites in the wider ecosanctuary. An adjustment period was also expected. This was assumed to be reflected in basking behaviour (skin temperatures reached and frequency of partial versus full exposure) following release into the enclosure. The results of this study can be used to better inform the release method used for green gecko translocations, and the design and suitability of future enclosures for *Naultinus* species throughout New Zealand.

The management implications and limitations of this research, as well as suggestions for future research directions, are discussed in Chapter 4. An additional part of this thesis focused on understanding the current green gecko enclosure designs that are in use today. This was considered essential to better understand the findings reported in Chapter 2 and to apply my research in the most effective way. This information was collected through a survey conducted as part of this thesis. The premise behind it, methods used and results are fully discussed in Appendix 1 and referred to in Chapters 1 and 3 of this thesis.

CHAPTER 2

The Establishment of Jewelled Geckos at Hard and Penned Release Sites within Orokonui Ecosanctuary, 8-11 Years Post Translocation

Introduction

A translocation is defined as the accidental or intentional human-mediated movement of wild or captive living organisms from one area to another. Such movements are becoming an increasingly used conservation tool for global biodiversity conservation (IUCN/SSC, 2013; Berger-Tal *et al.,* 2019). Historically, translocations have heavily focused on mammals and birds (Seddon *et al.,* 2005). It has been suggested that amphibian and reptile species may not be suitable for such movements, following the string of low success rates (Dodd and Seigel, 1991; Reinert, 1991). Germano and Bishop (2008) argued this point and found an increase in the number of successful amphibian and reptile translocations previously reported (if evidence of reproduction was found and the post-release monitoring period equalled the time taken for the species to reach sexual maturity). In some ways amphibians and reptiles appear to be better suited to conservation translocations than mammals and birds. This is because some captive bred reptiles (e.g., rattlesnakes; Chiszar *et al.,* 1993) appear to retain natural behaviours in captivity, and are therefore often viable candidates for translocation as well as wild conspecifics (Germano and Bishop, 2008). Of the reported failures, homing behaviour, large post-release dispersal and migration away from the release site were key contributing factors (Germano and Bishop, 2008). As ectotherms, reptiles are also particularly sensitive to the climate suitability and seasonal variation at the release site. This is because the external temperature and number of basking opportunities drives their metabolism and physiology (Angilletta *et al.,* 2004; Besson and Cree, 2011; Bellis *et al.,* 2020), and in some species, the sex ratio (e.g., tuatara; Jarvie *et al.,* 2014).

Translocation to offshore islands and protected areas on the mainland of New Zealand, has become a regularly used conservation tool for New Zealand reptiles (Towns *et al.,* 2016), including species of green gecko, (although with variable success: Sherley *et al.,* 2010; Knox and Monks, 2014; Flynn-Plummer and Monks, 2021). The translocation methods used

include a hard release (no supplementation), soft release (providing supplementary food, water or shelter) and a penned release (penning a founder population within a defined area for a pre-determined period of time before release; Knox and Monks, 2014; Richardson *et al.,* 2015; Knox *et al.,* 2017). To my knowledge, 13 green gecko translocations have been conducted throughout New Zealand: five penned and eight hard releases (Knox and Monks, 2014; *pers. comm.* Roger Wallace, involved with the Auckland green gecko translocation to Tiritiri Matangi Island, 2020; Flynn-Plummer and Monks, 2021). A key concern with the hard release method is that founder individuals may initially disperse large distances as they settle into the area. It is likely that high rates of dispersal will reduce the success of geckos finding conspecifics to reproduce with, as well as impeding the ability to monitor the success of the translocation (Knox and Monks, 2014; Berger-Tal *et al.,* 2019). The penned release strategy has been confirmed to significantly reduce the dispersal of jewelled geckos compared to hard released geckos, following release (Knox and Monks, 2014; Knox et al. 2017). Penning the founder population for at least four months is now considered the best practice for the translocation of green geckos (Monks *et al.,* 2017). It has since been applied to other species of green gecko (*Naultinus punctatus* (the barking gecko); Flynn-Plummer and Monks, 2021 and *Naultinus elegans* (Auckland green gecko) on Tiritiri Matangi Island, 2020; *pers. comm*. Roger Wallace, supporter of Tiritiri Matangi). There are however, no published reports of the long-term implications (>5 years) of release method used on dispersal rates of founder individuals (Fitzgerald *et al.,* 2015).

The Miller *et al.* (2014) standardised criteria of translocation success (based on case studies of New Zealand herpetofauna) is comprised of four stages. Stage 1: requires evidence of survival and growth of founder individuals; Stage 2: evidence of reproduction (excluding pregnant females released); Stage 3: population growth, where the number of captures or resights are greater than the release propagule (number of founders released) and there is evidence of reproduction by second generation animals; Stage 4: population viability, where the number of captures or resights per survey regularly exceed the release propagule, of which founder individuals make up a small proportion of captures and young individuals, a large proportion. With these criteria, Stages 1, 2 and 3 have been confirmed or predicted to be reached in translocations of tuatara, Duvaucel's gecko (*Hoplodactylus duvaucelii*) and several *Oligosoma* skink species (Towns *et al.,* 2016). None of the 13 green gecko translocations, however, have achieved population growth, or the establishment of a viable population (Stages 3 and 4; Flynn-Plummer and Monks, 2021).

All published post-release monitoring following a green gecko translocation has focused on short-term monitoring (up to one year following the release; Knox and Monks, 2014; Knox *et al.*, 2017; Flynn-Plummer and Monks, 2021). Unpublished data have been collected on the abundance of jewelled geckos sighted within Orokonui Ecosanctuary at each release site, for up to six years following release. However, the surveys have been sporadic, with the last surveys conducted in May 2016 for Site 1 and May 2018 for Sites 2 and 3 (*pers. comm.* Carey Knox, involved with the 2012 translocations and monitoring of the established populations). My study comprised the first intensive survey for jewelled geckos at all three release sites and the connecting suitable habitat since the last translocation in 2012.

This chapter aimed to determine the effect of penned and hard release translocation methods on the long-term dispersal of founder jewelled geckos, and the stage of translocation success reached 8-11 years following translocation. I had three main predictions: (1) I predicted that penned founder geckos would have dispersed a shorter distance than hard released founders 9 to 11 years following the translocations (adding to Knox and Monks', 2013 work). (2) I predicted that evidence of recent reproduction (neonates or juveniles) would be found at all three sites, because surveys were conducted during both winter and summer and adult jewelled geckos were known to occupy each release site. (3) I predicted that the populations at the two penned release sites would be close to or have reached Stage 3 of the Miller *et al.* (2014) criteria for translocation success (population growth), but not the population at the hard release site. This was based on the assumption that my first prediction was supported, and that reducing jewelled gecko post-release dispersal drives population establishment near the release site (and therefore aids geckos finding mates), long-term.

Methods

History of Translocations to Orokonui Ecosanctuary

Jewelled geckos were translocated from the Otago Peninsula population to three different locations within Orokonui Ecosanctuary through three separate translocations. The first was in 2009 (*pers. comm.* Mandy Tocher, conducted the 2009 translocation) and the second and third, in 2012 (Table 2.1; Knox and Monks, 2014; Knox and Rate, 2018). A fourth translocation occurred in 2014, although following a pen leak and concerns about poaching within the ecosanctuary, these geckos were removed from the ecosanctuary and released at a different site. The 2009 and one of the 2012 releases used a penned release method (where

translocated individuals were first contained within a polythene plastic pen for 9-12 months before the pen was removed) to minimise post-release dispersal (M. Tocher, unpubl. data; Knox and Monks, 2014). No pen was used for the 2012 hard release group. Demographics of the source populations for each translocation are summarised in Table 2.1.

Monitoring population growth and dispersal throughout the sanctuary has been difficult due to the cryptic nature of the species and the tall mānuka habitat. Furthermore, the rate of population growth for jewelled geckos is limited by their slow life history (reaching sexual maturity at three years old, having a low annual reproductive output of up to two offspring, and high longevity; Wilson and Cree, 2003; Cree and Hare, 2016a). However, sightings of young, sub-adult and founder individuals have occurred every year following the translocations and in new areas of the sanctuary. This provides evidence that founder individuals have successfully reproduced and are colonising new areas (Knox and Monks, 2014; Knox *et al.*, 2019). In a 2018 survey, 12 founder geckos from the 2012 translocation were re-sighted, indicating that these geckos have survived six years following the translocation (Knox and Rate, 2018). Dispersal over long distances has also been observed with one gecko sighted 2.1 kilometres away from where it was photographed as a neonate three years earlier (Knox and Rate, 2018). From these annual survey data, it is expected that there are over 200 jewelled geckos throughout the ecosanctuary today (Knox and Monks, 2014; Knox *et al.*, 2019).

Survey Sites

Specific details on the location of gecko sightings and release sites are not provided due to concerns around the illegal poaching of this species. The 2009 penned translocation was conducted at Site 1. This is the second largest site and ~34% of the habitat is too dense to survey. Site 2 is the largest and includes the 2012 hard release site and the failed 2014 penned site. It has a similar proportion of inaccessible vegetation to site 1 and is located ~230 m from Site 1. Site 3 includes the 2012 penned release site, where the largest number of geckos were released (42 geckos). It is approximately 181 m from Site 2 and the furthest from Site 1 (~525 m). Around 50% of the habitat here was unable to be surveyed (Table 2.2). The distances between sites were estimated in Google Earth using the distance and area tool, and measured from the middle of each site or the middle of the release pen at Site 3. The area of each site was estimated using the measure distance and area tool in Google Maps. Mānuka and kānuka trees and dense *Coprosma* shrubs dominate the vegetation at all sites. The habitat structure at Site 1 is currently much taller than the other sites, with densely grouped kānuka

Table 2.1. A summary of the release method used and the population size, sex ratio and age structure of the three founder populations of jewelled geckos translocated to Orokonui Ecosanctuary. **F-A** = Female adult, **M-A** = Male adult, **F-SA** = Female subadult, **M-SA** = Male subadult, **J** = Juvenile, individuals were too young to be able to be reliably sexed.

Translocation	Penned or hard release area	Time penned before release	Founder population size	Sex Ratio			Age structure		
				F (Pregnant)	M	UC	A	SA	J
2009 Penned (Site 1)	10 pens – 14-48m^2	12 months	36	16 (15)	14	6	30	0	6
2012 Hard release (Site 2)	206m^2	-	11	6 (0)	5	0	11	2	0
2012 Penned (Site 3)	1 pen - 665m^2	9 months	42	21 (19)	6	15	24	3	15

trees ~7 m tall (compared to a maximum height of ~4.5 m at Sites 2 and 3; Figure 2.1). Site 1 has also experienced the greatest habitat growth and change since the translocation (*pers. comm.*, Elton Smith, conservation manager at Orokonui Ecosanctuary).

Day Surveys

Between 14 June 2020 and 7 February 2021, I conducted 75 one-day surveys on sunny days when geckos were expected to be basking (Duggan, 1991). I spent 261 h searching but with the help of Orokonui staff and volunteers on some of the survey days, this totalled to 392-person h of searching (Table 2.2). The optimal basking time varied between seasons; in winter, geckos took longer to warm up in the mornings and to emerge from vegetation to bask, and there were fewer sunny hours throughout the day. Therefore, the timing of surveys was subject to the season, to target times of day when geckos were likely to be out basking. Surveys were subsequently carried out between 1000-1500 NZST in early winter, 1100-1400 NZST by mid to late winter and from 0900 NZDT onwards during spring and summer, as the mornings became warmer. The duration of each survey was subject to the weather throughout the day and time available.

The search time at each site differed due to the area, habitat complexity and habitat accessible at each site. In addition, the target survey area changed over the fieldwork period. While geckos of all life histories were searched for to address the aims of Chapter 1, sighting subadults was of particular interest as 10 subadults were sought from within the ecosanctuary for transfer to Orokonui's new jewelled gecko breeding and viewing enclosure. An additional 10 subadults were sought to form the "free-roaming" group of geckos for comparison (discussed in Chapter 3). Surveys conducted during the first fieldwork period (14 June – 3 September 2020) focused on Site 3, as it was the area with the highest known density of jewelled geckos within the ecosanctuary and was expected to be the sole source of geckos for Chapter 3. Within the first half of this fieldwork period, very few subadults were located; therefore, I began to search Site 1 and Site 2 when possible. Site 2 was often surveyed on the way to Site 1 and when leaving the ecosanctuary; Site 3 was surveyed the least due to its distance from the other sites. After this first fieldwork period, four subadults out of 30 geckos had been found. It was clear that additional areas of the ecosanctuary would have to be searched to locate enough subadult geckos to form both groups. From 16 September 2020 – 7 February 2021, all three sites and the connecting suitable habitat were surveyed regularly.

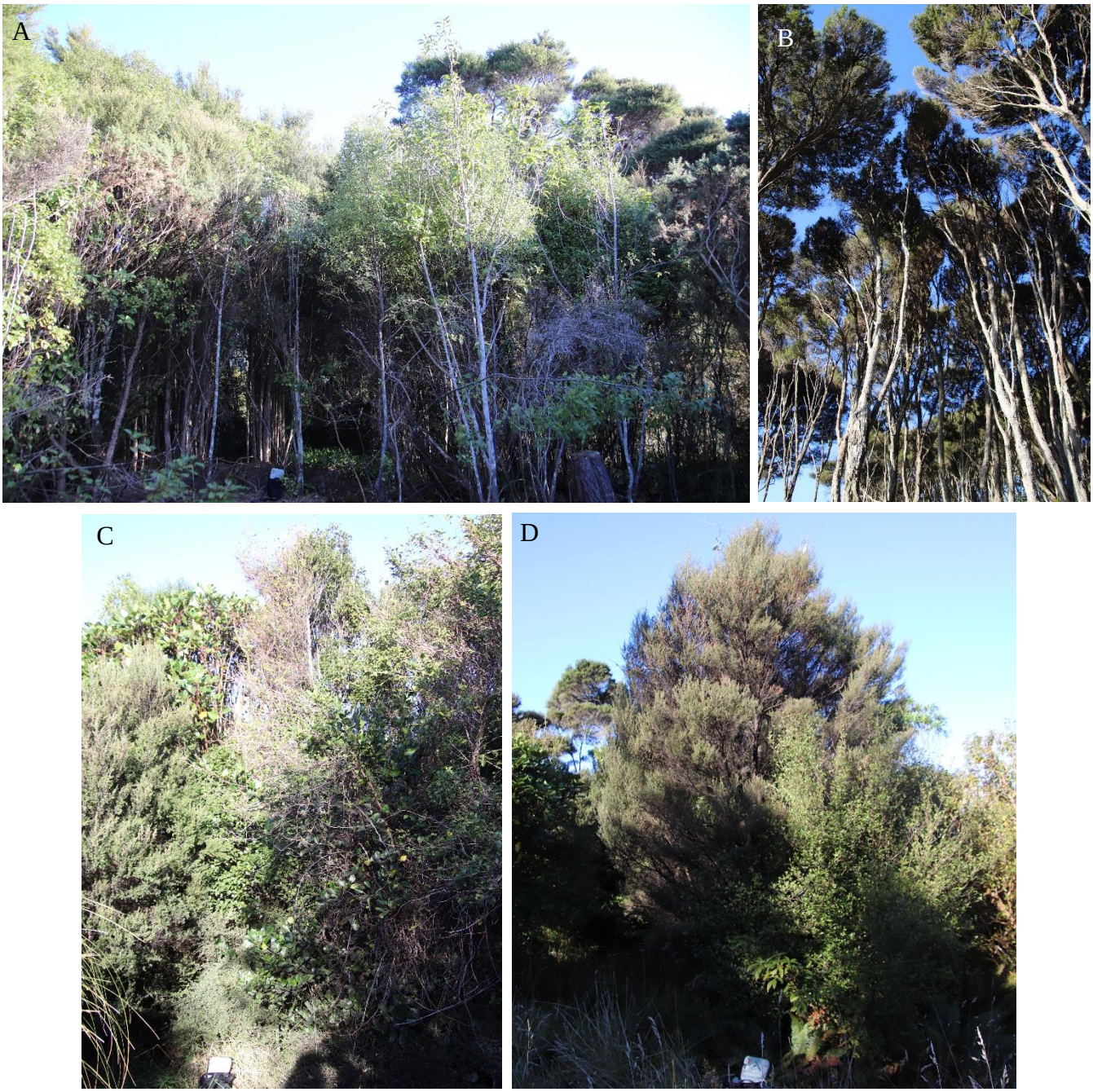


Figure 2.1. The tallest suitable jewelled gecko habitat present at the three jewelled gecko release sites within Orokonui Ecosanctuary. A-B: 2009 penned release site (Site 1, ~7 m tall), C: 2012 hard release site (Site 2, ~4.5 m tall) and D: 2012 penned release site (Site 3, ~4.5 m tall). All photos are of habitat within or immediately surrounding the hard and penned release areas.

During each survey, the suitable habitat at each release site was visually searched, as was the surrounding accessible vegetation within a ~50 m radius of the release sites. The suitable habitat when travelling between sites was also searched. When first sighted, individuals were not marked but were photographed using a Canon 800D camera and a Tamron 18-400 mm lens. Individuals were identified using their unique natural patterns on the dorsal surface (Knox *et al.*, 2013). The life history stage of each gecko sighted was visually determined as a neonate/juvenile, subadult or adult. When possible, a photo of the lower region of the body was taken to determine the presence (male) or absence (female) of a hemipenal sac. Neonates, juveniles and young subadults were unable to be sexed. As most geckos were not handled, the reproductive state of females was unable to be confirmed via palpation. Instead, photos were analysed by myself and Alison Cree; females that looked potentially pregnant to both of us were categorised as "probably reproductive." This category accommodates any females who appeared pregnant due to large vitellogenic follicles or early pregnancy (which were thought to be difficult to distinguish without palpation). When each gecko was first sighted, a GPS location was recorded with at least 5 m accuracy on a GARMIN GPSmap 60CSx using the New Zealand Transverse Mercator (NZTM) coordinate system.

A photo library exists that contains the photos of every individual jewelled gecko translocated to the ecosanctuary and all ecosanctuary-born geckos sighted during annual surveys prior to my study; this was provided by Carey Knox. Using this library, geckos were identified as original (translocated in 2008/2009 or 2012), previously sighted (but sanctuary-born) or new geckos (new to the photo records and therefore not seen before). To assess the influence penning had on the dispersal of founder individuals 8-11 years post-translocation, I compared the proportion of founders resighted between sites using a chi-square test. To determine the influence penning has had on the distribution of the established population sighted (in relation to the pen boundary) 9 years following release, I compared the proportion of originally released, previously seen and new geckos first sighted within and outside the pen boundary using a chi-squared test. For both chi-squared tests, a Cramer's V statistic was calculated to indicate the effect size: ≤ 0.3 = small, 0.31-0.5 = medium and >0.5 = a large effect size.

In order to test if detectability (sightings per person hour of searching) of jewelled geckos differed between the season visual searches were conducted in (winter, spring or summer), a one-way ANOVA was used. To run the analysis, days when zero geckos were sighted were

removed (3 days in spring and 13 in summer). Data were normalised using the log transformation. Effect size was estimated with the partial eta squared value: 0.05 – 0.1 = small, 0.3-0.5 = medium and >0.5 = large. The model was then checked using the Levene's test in R Studio.

Mapping

This chapter utilises the GPS locations recorded over both fieldwork periods (June to early September 2020 and late September 2020 to February 2021). The location of each gecko when first sighted was mapped in QGIS. Points were colour coded to visually display the distribution of geckos throughout the sanctuary, and their origin (originally translocated, previously sighted or new individuals). GPS locations of the pen and hard release boundaries were added.

Measuring post-release dispersal

The exact release locations for geckos from the 2009 and 2012 translocations were not recorded. Instead, the GPS location where geckos were first sighted following the 2012 hard and penned releases (from Carey Knox's records), were used as a proxy for the release positions. These GPS locations were used to estimate post release dispersal in R (Package GeoDist; Padgham and Sumner, 2020). The distance between gecko locations when first sighted in this study and the 2012 pen boundaries were estimated using the measure distance and area tool in Google Maps.

To assess the influence the release method used (penned versus hard release) had on the long-term dispersal (linear distances between the two sightings) of founder individuals resighted, I compared dispersal distances of founders from the 2012 penned and hard release translocations. Only one founder was sighted at Site 1, therefore the analysis did not include dispersal distances from the 2009 penned translocation as it would violate the assumption of equal variances. The dispersal distance data were tested for normality and equality of variances by examining boxplots and histograms. Data was fourth-root transformed to meet these requirements. A two-way ANOVA was used to test the influence of the translocation method used (2012 penned release or hard release) and the sex of originally translocated geckos (predictor variables) on the estimated dispersal distance (response variable). Effect sizes were estimated with the partial eta squared value. The model was then checked for homogeneity of variances using the Levene's test in R Studio.

Table 2.2. A summary of the demographics (sex ratio, life history stage and origin of individuals) of each gecko population at Sites 1, 2, 3 and the new sites (4 sites) combined. The total site area and area of each site which was accessible for surveying (m^2) is included. **F-A** = Female adult, **M-A** = Male adult, **F-SA** = Female subadult, **M-SA** = Male subadult, **N/J** = Neonate or Juvenile, **OR** = Originally released during the 2009 or 2012 translocations, **PS** = Previously sighted (and born in the ecosanctuary), **NE** = New to the photo records, **UC** = Status is unconfirmed due to poor photo quality. * refers to an individual found outside the ecosanctuary that was caught and released at site 1. The person hours spent surveying is an estimation and includes the hours contributed by volunteers and members of Orokonui staff.

Sites	**Total Site Area (m^2)**	**Accessible Area (m^2)**	**Sex and Life History Stage**							**Origin**				**Total Sighted (and Founder Size)**	**Person Hours Surveying**
			F-A	**M-A**	**F-SA**	**M-SA**	**N/J**	**UC Sex**	**UC Sex and LHS**	**OR**	**PS**	**NE**	**UC**		
Site 1	5,091	3,365 (66%)	2	3*	0	1	7	1A 2SA	1	1	0	11*	5	17* (30)	51.9
Site 2	6,067	3,737 (62%)	4	4	1	1	0	0	0	3	0	7	0	10 (11)	42.4
Site 3	4,717	2,384 (50%)	10	11	1	2	8	4A 4SA	0	9	4	24	3	40 (42)	201.2
New Sites	-	-	3	1	0	0	4	2A 1SA	1	0	0	10	2	12	73
Totals	-	-	19	20	2	4	19	14	2	13	4	53	10	80	392.6

Results

On average, surveys lasted 3 h 35 min, and ranged from 1 h 20 min to 6 h. The greatest search effort went into Site 3, followed by the new sites, Site 1 and Site 2 (Table 2.2). Site 3 was the only one regularly surveyed across all three seasons. While a new gecko was sighted on the 64th visual search (of 75 searches), 95 % of the total number of individual geckos sighted at Site 3, were found within the first 36 searches (after 159-person h of searching; Figure 2.2).

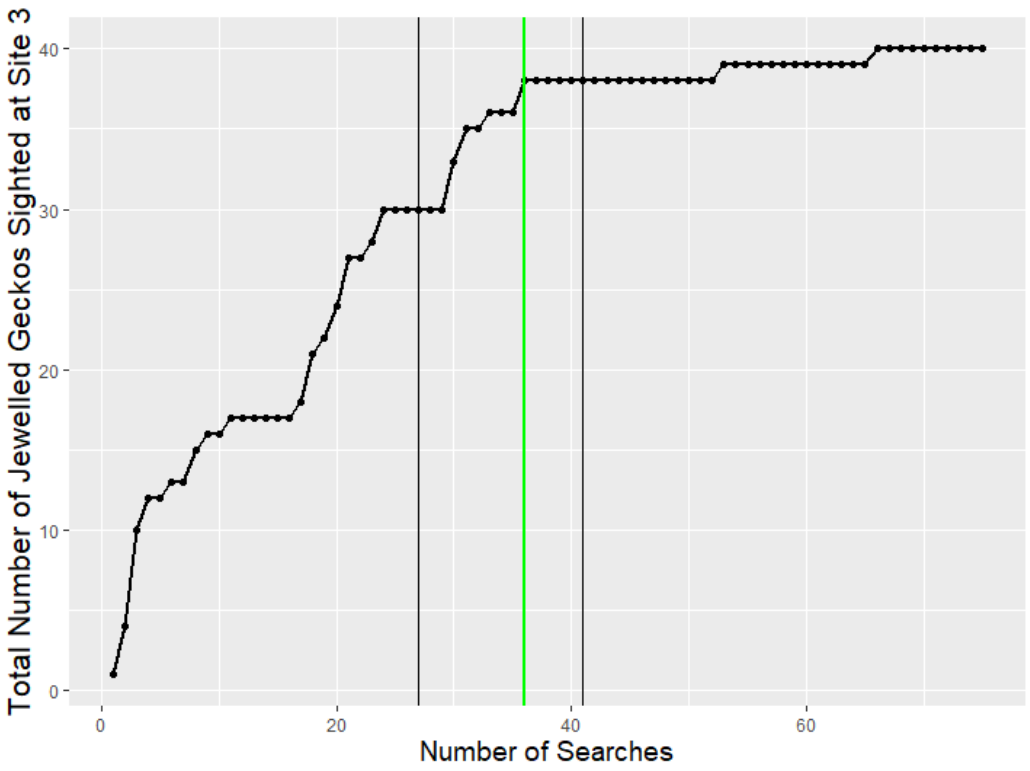


Figure 2.2. A cumulative population curve for Site 3 (the 2012 penned release site) for the 75 visual searches conducted between 14 June 2020 and 7 February 2021. Black lines indicate the transition from winter (surveys conducted from 14 June to 29 August) to spring (from 2 September to 3 November) and spring to summer (from 15 December to 7 February). The green line indicates the point at which 95% of total geckos sighted at Site 3, had been observed by. This was after 159 (of 201) person h of searching.

In total, 80 individual geckos were found throughout the ecosanctuary. Established populations were sighted at each of the 2009 and 2012 translocation sites and in four new sites (>50m from hard release or pen boundaries) (Figure 2.3). The ecosanctuary population

as a whole had an even sex ratio (21 F:24 M) and adults were most frequently observed, followed by neonates/juveniles and then subadults (Table 2.2). Five females were categorised as probably reproductive (one female at both Sites 1 and 2 and three females at Site 3). Fifty-two geckos were identified as new to Orokonui's photo records, four were previously sighted geckos (but born within the ecosanctuary) and 13 geckos were confirmed to be individuals originally released at that respective site (Table 2.2). Sixteen geckos were unable to be sexed, and the life history stage of two geckos and the origin of ten were unable to be confirmed due to poor photo quality or the absence of photographic evidence.

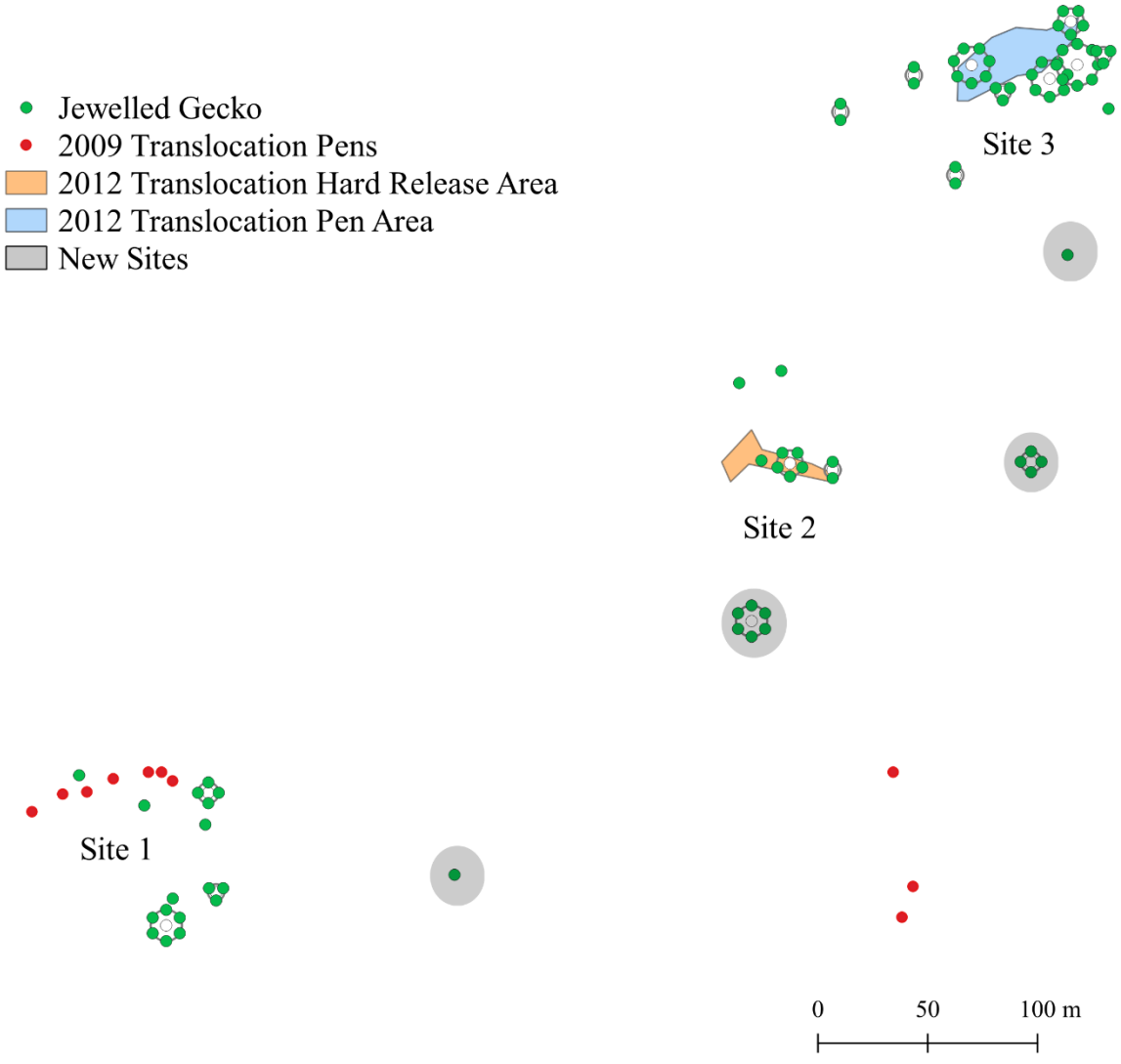


Figure 2.3. A map illustrating the distribution of jewelled geckos throughout Orokonui Ecosanctuary. Geckos were sighted between May 2020 and February 2021. Geckos first sighted within 5 m of one another are joined in a ring formation around a white circle which pinpoints the location of the first sightings. 2009 pens ranged in size from 14-48m^2. The three

2009 release pens in between Sites 1 and 2 held only four geckos and previous surveys suggest the founder individuals have not remained in this area (*pers. comm.* Elton Smith, conservation manager at Orokonui Ecosanctuary). The area surrounding these pens were subsequently not visually searched in this study and not considered part of Site 1.

Seventeen geckos were located at Site 1 (2009 penned release). Two adult females and three adult males were identified. Seven geckos were located within 20 m of the nearest pen used in 2009. The remaining ten geckos were within 60-80 m of the penned areas (Figure 2.4). The smallest population was found at Site 2 (which included the 2012 hard release site and the 2014 failed penned site) with ten geckos located (Figure 2.5). Interestingly, while the area surveyed at Site 2 was approximately 3,737 m^2, eight of the ten geckos located here were within a 40 m^2 strip of land, with 5 geckos found on the same shrub (*Pittosporum tenuifolium*). The other two geckos were found within 25 m of the nearest hard release boundary (Figure 2.5). The population at Site 2 consisted of mainly adults and an equal sex ratio. It was also the only site in which no neonates were detected. Three geckos were identified as founders (two from the hard release translocation and one from the failed penned translocation). The other seven were new to Orokonui's photo records (Table 2.2).

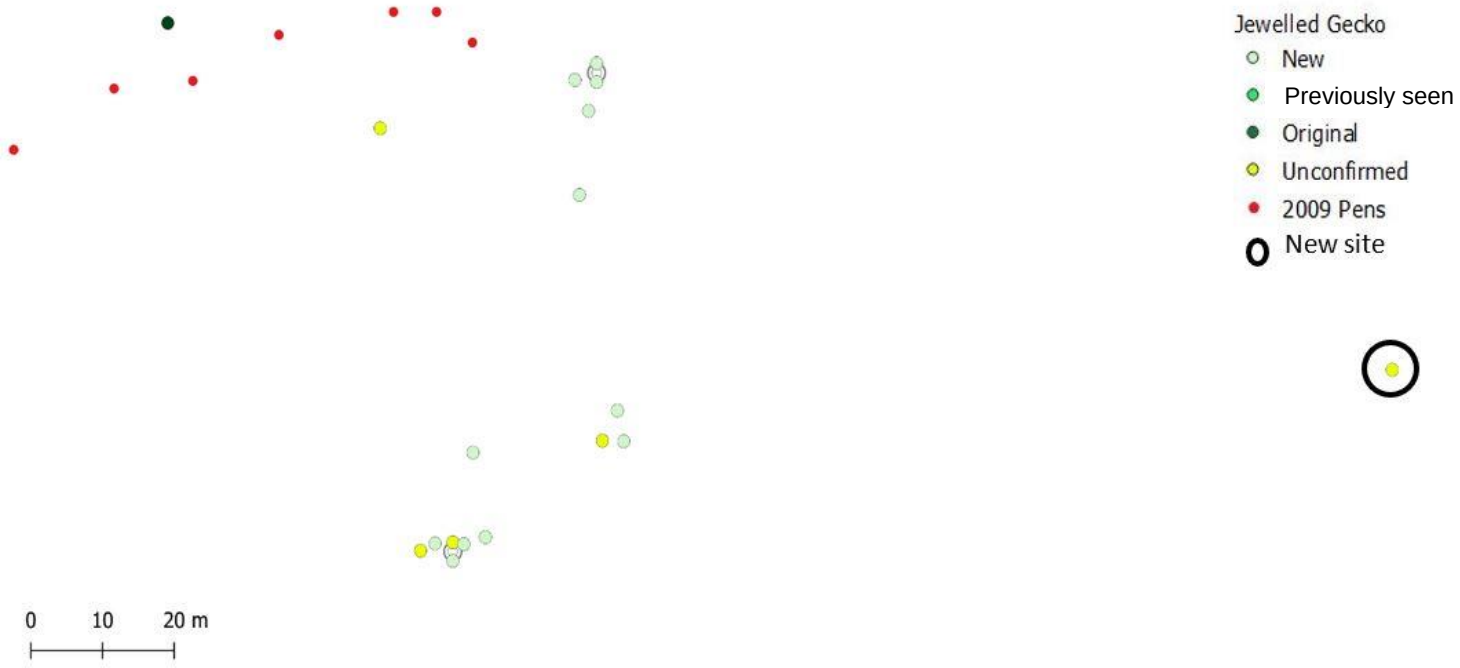


Figure 2.4. A map illustrating the spatial distribution and origin of jewelled geckos sighted

between May 2020 and February 2021 at Site 1 (the 2009 penned release site). Geckos first sighted within ~1 m of one another are joined in a ring formation around a white circle which pinpoints the location of the first sightings. Dots are colour coded according to the origin of geckos: new to the photo records, previously sighted (but sanctuary-born) or originally released. The 2009 pens ranged in size from 14-48 m^2.

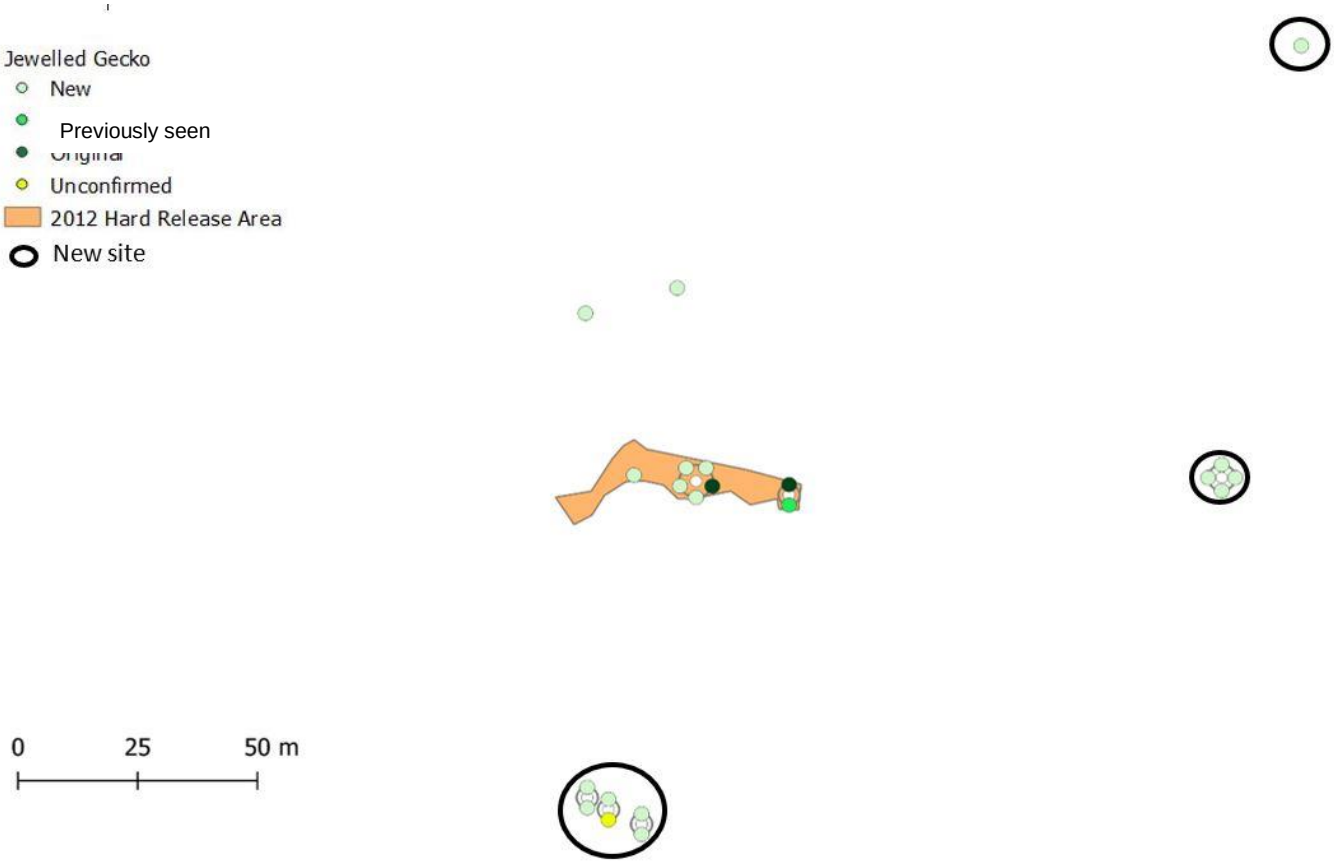


Figure 2.5. A map illustrating the spatial distribution and origin of jewelled geckos at Site 2. Geckos were sighted between May 2020 and February 2021. Geckos first sighted within ~1 m of one another are joined in a ring formation around a white circle which pinpoints the location of the first sightings. Dots are colour coded according to the origin of geckos: new to the photo records, previously sighted (but sanctuary-born) or originally released.

The most geckos (*n* = 40) were found at Site 3; 12 were located inside the 2012 penned area. The distribution of the remaining geckos varied: 24 geckos were sighted within 25 m of the closest release pen boundary edge, and the remaining 5 geckos were within 50 m of the closest boundary edge. All previously sighted and original geckos were first sighted either inside the pen boundary (four geckos) or within 25 m of it (eight geckos), except for one previously sighted gecko, located ~42 m west of the closest pen boundary edge. Geckos new

to the photo records were dispersed throughout the site and made up a large proportion of the geckos that were more widely distributed (Figure 2.6). The age structure and sex ratio at Site 3 was relatively equal (10 adult females, 11 adult males) and a large proportion of adults were sighted (25 adults) compared to subadults and neonates/juveniles (7 and 8).

Twelve geckos were sighted at four new jewelled gecko sites (Figures 2.2 and 2.3), all of which were identified as new to Orokonui's photo records (Table 2.2). Each new site was located between the three main release sites. There was however, no evidence of geckos moving between sites as all previously sighted or original geckos were located within 45m of their release site or release location when first sighted in this study.

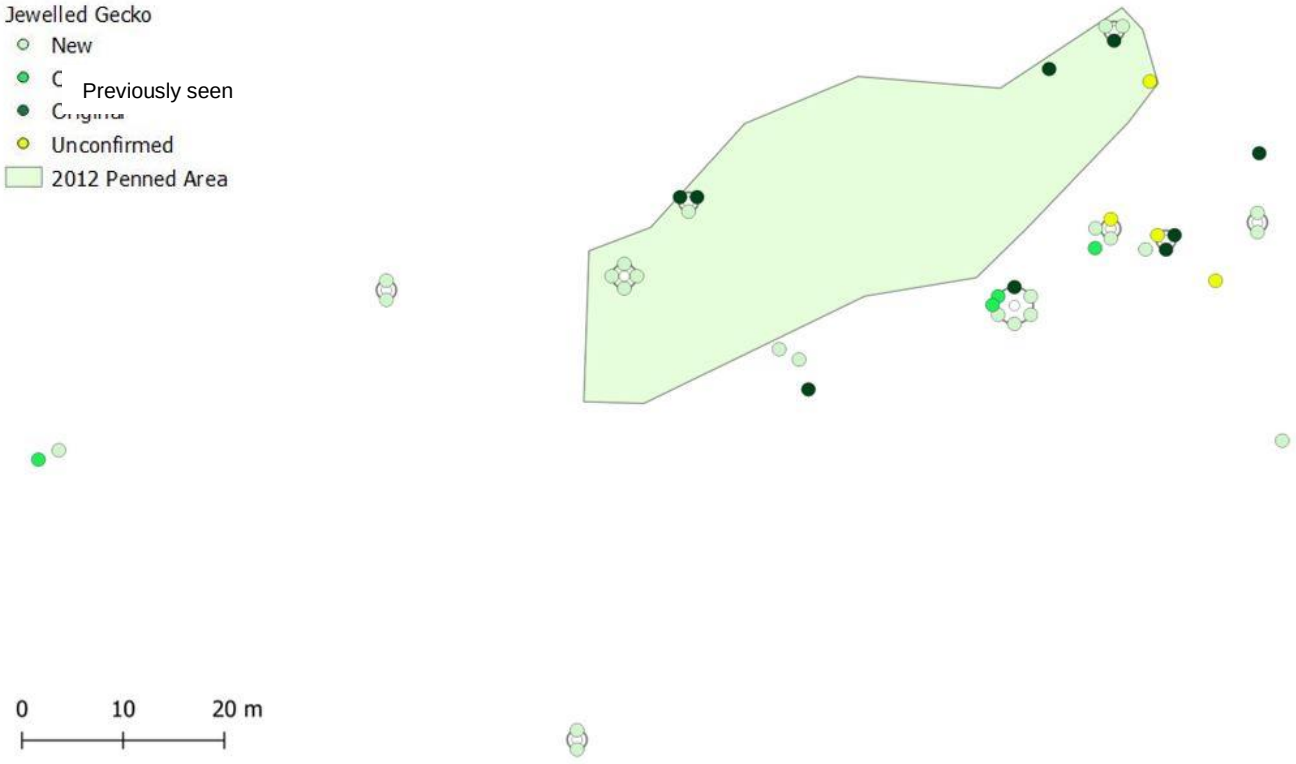


Figure 2.6. A map illustrating the spatial distribution and origin of jewelled geckos at Site 3. Geckos were sighted between May 2020 and February 2021. Geckos first sighted within ~2 m of one another are joined in a ring formation around a white circle which pinpoints the location of the first sightings. Dots are colour coded according to the origin of geckos: new to the photo records, previously sighted (but sanctuary-born) or originally released.

In comparing the age structure and sex ratio of the sighted populations at each release site, it is evident that adults made up a large proportion of sightings (47% at Site 1, 80% Site at 2

and 62.5% at Site 3). The proportion of neonates however, differed greatly between sites (41.2% at Site 1, 0% at Site 2 and 20% at Site 3) and Site 1 appeared to have the youngest age structure of the three sites with 52.9% of the population sighted being a neonate/juvenile or subadult (Table 2.2). The proportion of founders resighted differed between release sites but were similar between the 2012 hard and penned release sites (Site 1 = 3%, Site 2 = 27%, Site 3 = 22 %; Table 2.3). Similarly, the proportion of geckos sighted compared to the propagule size was similar for both 2012 sites (90.9% at Site 2 and 95% at Site 3) but lower for the 2009 site (Site 1; 56.7%). The likelihood of resighting an original gecko, was found to be independent of the translocation method used (χ^2= <0.001, df = 1, P=1, with a very small effect size of <0.001). In addition, gecko sightings inside or outside the 2012 pen boundary was independent of gecko origin (χ^2 = 2.63, df = 2, P = 0.31, with a small effect size of 0.27).

The mean dispersal distance for 2012 penned founders was 42.2 m (ranging from 1 m to 81.7 m). The mean hard release dispersal distance was 41 m (ranging from 21.8 m to 60.3 m; Table 2.3). One of these geckos found at Site 2 was originally released as part of the failed 2014 translocation and travelled approximately 97.7 m between sightings, the greatest distance for any of the original geckos. Mean dispersal distances for males (46.8 m, ranging from 14.4 m to 81.7 m) and females (34.8 m, ranging from 1m to 97.7 m), did not differ statistically (and had a small effect size: Partial eta squared value = 0.28), F statistic = 2.70, df = 1, P = 0.14). There was no statistically significant difference between the translocation method (2012 hard release and 2012 penned release) and the linear distance travelled between the two sightings (partial eta squared however revealed a medium effect size of 0.44, F statistic = 1.16, df = 3, P=0.39). Sightings per unit effort (person hour of searching) at Site 3 however, were significantly higher in winter than spring and summer (partial eta squared = 0.31, F = 23.42, P = <0.001, Figure 2.7).

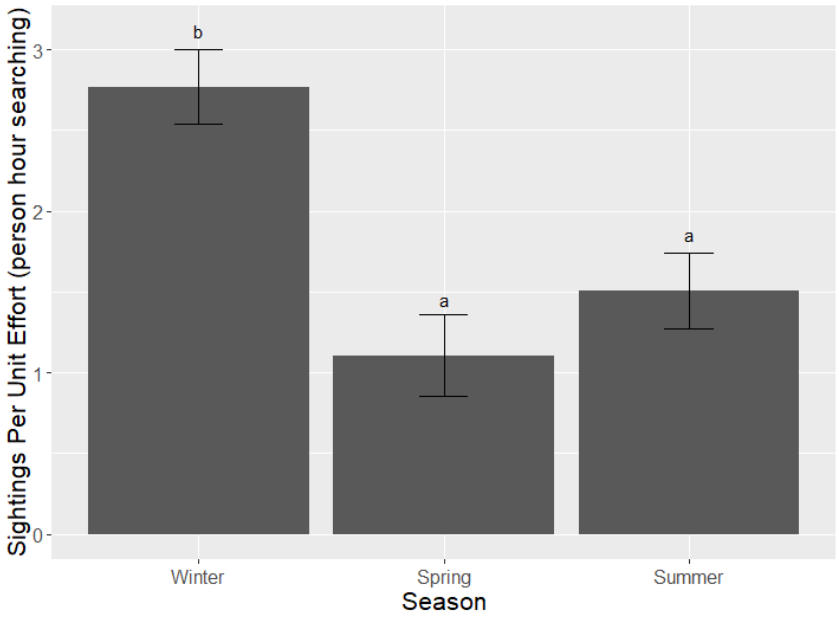


Figure 2.7. Mean sightings per unit effort at Site 3 across winter 2020 (14 June – 29 August, 26 searches), spring 2020 (2 September – 9 November, 14 searches) and summer 2020-2021 (15 December 2020 – 7 February 2021, 35 searches). Bars represent standard error. Letters above bars represent post-hoc test results (Tukey test).

Table 2.3. The linear dispersal distances of originally translocated jewelled geckos resighted within Orokonui Ecosanctuary between June 2020 and January 2021. Dispersal was calculated from the location where first sighted following release (rather than the exact release position, due to data unavailability).

Gecko ID	Sex	Translocation	Date Translocated (or pen removed)	Date of first resighting following translocation	Date of first resighting between 2020-2021	Linear Distance Travelled (m)
1MA2	M	2009 Pen	February 2009	April 2009	November 2020	31.6
2FA1	F	2012 Hard Release	28 September 2012	November 2012	July 2020	21.8
2FA4	F	Failed 2014 Pen	8 October 2013 (into pen)	April 2015	October 2020	97.7
2MA4	M	2012 Hard Release	28 September 2012	April 2013	January 2021	60.3
3FA1	F	2012 Pen	28 September 2012	March 2013	June 2020	64.6
3FA4	F	2012 Pen	28 September 2012	September 2012	July 2020	1
3FA5	F	2012 Pen	28 September 2012	October 2012	July 2020	6.1
3FA9	F	2012 Pen	28 September 2012	April 2015	October 2020	17.3
3MA2	M	2012 Pen	28 September 2012	October 2012	July 2020	14.4
3MA3	M	2012 Pen	28 September 2012	October 2012	July 2020	55.7
3MA4	M	2012 Pen	28 September 2012	September 2012	July 2020	15.3
3MA6	M	2012 Pen	28 September 2012	September 2012	August 2020	81.7
3MA7	M	2012 Pen	28 September 2012	September 2012	August 2020	68.4

Discussion

A total of 80 geckos were sighted throughout Orokonui Ecosanctuary. The largest jewelled gecko population detected in my study was at the 2012 penned release site (40 individuals at Site 3). The smallest was at the 2012 hard release site (10 individuals at Site 2). These differences between sites are likely a result of the release method used, time since release and propagule size (Table 2.1), in addition to differences in habitat structure. Twelve geckos were found in new sites (locations >50m from the nearest release site boundary). Thirteen originally translocated geckos were resighted, with at least one at each release site and 53 geckos were new to the photo records. There was no statistical effect of the release method used or sex of originally translocated on gecko dispersal rates (linear distance between the two locations) 8-11 years post-translocation. However, sample sizes (of founders resighted) were limited. The medium effect size for the relationship between the translocation method and dispersal distance, suggests there may be some biological significance of these findings. Below I discuss the role sighting bias has played in the observed patterns, assess the stage of success each of the translocations are at using the criteria provided by Miller *et al*. (2014). I compare the established populations sighted at the hard and penned 2012 release sites and those at the 2009 and 2012 penned sites and discuss the long-term dispersal patterns observed.

Sighting Bias Present

Detection probability can be influenced by a large range of factors such as variation in individual appearance (pattern, sex, age, size or social status), observer experience, variation in habitat structure complexity and weather conditions at the time of survey (Dodd and Dorazio, 2004; Weir *et al.*, 2005; Lardner *et al.*, 2015). The differences in habitat structure between sites in this study, created a sighting bias towards sighting more geckos at Site 3. The habitat that immediately surrounds the Site 1 penned areas is now dominated by tall mānuka trees, with the canopy reaching ~7m high (compared to a maximum height of ~4.5m at Sites 2 and 3). This severely hinders the observer's ability to locate geckos in that area. One gecko at Site 1 was observed through binoculars basking ~5.2m up a mānuka tree. It is possible that more individuals use the same habitat, and therefore the number of geckos observed in my study, especially at Site 1, is likely to be an underestimate.

Adults made up a much larger percentage of total geckos sighted in comparison to subadults and neonates/juveniles throughout the ecosanctuary. Observer bias has likely contributed

towards these numbers because adults are larger, and therefore stand out against the vegetation more than subadults, juveniles and neonates do. Thus, I am unable to conclude that there are more adults present within the ecosanctuary because these differences in detectability mask the ability to determine any true differences.

The total number of individual geckos sighted is also likely to be an underestimate as visual searches were only able to focus on the edges of vegetation, which often formed the perimeter of dense and inaccessible habitat. Furthermore, the observer's view is restricted to visible edges of vegetation so geckos basking higher than the observer can see, or in dense pockets of vegetation, will be missed. The low resighting rate (with 30 geckos only sighted once and 12 geckos sighted twice), reinforces the idea that geckos are using habitat not visible to the observer. This may explain why the distribution of geckos at Site 2 appears to be closely tied to the hard release site.

Assessing Stage of Translocation Success at all Release Sites

Stage 2 of the Miller *et al.* (2014) criteria for translocation success (evidence of reproduction), was fulfilled at all three release sites 12 – 33 months following release (unpublished data, Carey Knox). Interestingly, the populations detected at the 2012 hard and penned release sites appear to be at very similar stages of success. With two to three more gecko sightings, it can be confirmed that Sites 2 and 3 have reached Stage 3 (sighting more individuals than were released; see Table 2.4). With the sighting bias discussed above, it is highly likely that both sites have already reached Stage 3. Fourteen more sightings are required for Site 1 to reach this stage. However, it is difficult to determine to what extent the habitat structure will hinder the ability to monitor and determine the long-term success of this penned translocation. This highlights the potential need for the Miller *et al.* (2014) criteria to accommodate cryptic species, like green geckos. With species where detection is low, it is rare that the number of individuals sighted represents the number of individuals present within a population (Thompson, 2004). To take this disparity into account, a population abundance estimate that exceeds the propagule size, could also be considered as viable evidence that Stage 3 had been reached.

The pace at which each stage is reached by New Zealand lizards is heavily driven by the species' life history (Towns *et al.,* 2016). However, the ability to detect these stages depends on the effort invested and the level of detectability (influenced by how cryptic the species is and the habitat structure and complexity at the release site; Towns *et al.,* 2016; Bell and

Herbert, 2017). Stage 4 represents a self-sustaining, viable population and is confirmed through regular high sighting rates where young individuals make up a large proportion, and founder individuals, a low proportion of the sightings, or if a low probability of extinction is estimated (Miller *et al.*, 2014). New Zealand lizard species translocated to predator free offshore islands, have been found to reach Stage 3 between 5 years (*Oligosoma whitakeri*) and 10 years (*O. townsi*), while a translocated population of *O. oliveri* had still not reached this stage 17 years following release (Towns *et al.*, 2016). This is likely a reflection of the slow life histories many New Zealand lizards have (with high longevity, late sexual maturity and a low reproductive output being common; Van Winkel *et al.*, 2018). Consequently, reaching Stage 4 appears to take even longer with full replacement of the originally translocated population predicted to take between 20-30 years for *Oligosoma* spp., and potentially 100 years for tuatara (*Sphenodon punctatus*; Towns *et al.*, 2016). The key benefit of confirming Stage 4 in a translocated population is it gives confidence that the population size is not only increasing, but also stable, and recruitment is successful (Miller *et al.*, 2014).

The need to monitor translocated populations long-term and to determine and report causes of failure is widely encouraged (Germano and Bishop, 2008; Berger-Tal *et al.*, 2019). I therefore recommended that periodic searches are conducted at the three jewelled gecko release sites, to determine if and when these stages are reached. It is difficult to predict when Stage 4 will be reached, especially considering the low resighting rates reported in this study, which suggest geckos are utilising habitat not readily visible to the observer, and the detectability challenges associated with jewelled geckos. However, this knowledge will strengthen the release design used and can assist in shaping future green gecko translocations to protected areas and the long-term monitoring program used (namely effort invested and time between surveys).

Table 2. 4. Stages of translocation success of jewelled gecko achieved at the three release sites within Orokonui Ecosanctuary. Site 1 = 2009 penned release, Site 2 = 2012 hard release, Site 3 = 2012 penned release. Table adapted from Miller *et al.*, 2014.

	Site 1	**Site 2**	**Site 3**
Date of Pen Removal or Hard Release	February 2009	September 2012	September 2012
Stage 1: Survival and growth of individuals	✓	✓	✓
Stage 2: Evidence of reproduction (not from gravid females released)	✓ November 2011	✓ September 2013	✓ October 2012
Stage 3: Population growth (capture of more individuals than were released)	14 more sightings needed	Likely reached by 2021 - 2 more sightings needed	Likely reached by 2021 - 3 more sightings needed
Stage 4: Viable population (consistently high number of resights, young animals regularly sighted or low probability of extinction)	Not yet detected	Not yet detected	Not yet detected

Comparison between Hard versus Penned Releases from 2012

The penned release site remains home to a large population of jewelled geckos eight years following the removal of the pen, with 40 individuals located within this site, including eight neonates. I hypothesised that evidence of greater population growth (sighting more individuals than founders) would be found at Site 3 compared to Site 2 due to the penned method used and the larger propagule size. The number of pregnant females released was also thought to be a contributor as 19 pregnant females were penned in 2012, but no pregnant females were hard-released. However, the proportion of geckos sighted compared to the founder population size was similar for both sites, as was the proportion of founder individuals resighted. This result is even more surprising when compared to the reported failure of previous hard-release translocations of green geckos (between 1994 and 2010) with negligible post-translocation resighting rates (0-1 geckos; Shaw, 1994; Sherley *et al.*, 2010; McClure, 2011, Knox and Monks, 2014). It is evident, however, that both the release method and propagule size differ between Sites 2 and 3, which makes it difficult to determine the extent of the influence the release method used has had on the translocation success at Site 3.

Site 2 was the only site where neonates were not detected (although one female sighted here was considered probably reproductive in both October 2020 and February 2021). Two subadults were sighted, which could be an indication that reproduction has occurred at the site within the last two years. However, these subadults could have dispersed into Site 2 from other sites. Only one gecko was found in the 2014 penned area (considered a failed translocation). This is rather surprising considering ≤ 11 individuals were unable to be recaught and relocated following the pen leak (Knox *et al.*, 2017). Therefore, it could be considered to be a similar translocation to the 2012 hard release. It is also evident, that geckos from the 2012 hard-release translocation (~ 75 metres away), appear to have not dispersed into the failed 2014 area, despite the abundance of suitable *Coprosma* habitat present. The number of sightings made at Site 2 in this study indicates that Stage 3 of translocation success has or is close to being reached. This translocation can therefore be considered the first hard-released green gecko population that has established. This establishment emphasises the significant role habitat suitability plays in assisting establishment and the importance of high search effort during post-release monitoring in confirming the establishment of a population.

My findings suggest that the release method used did not influence the outcome of the translocation (i.e., whether a population established or not; although there will be a natural

threshold required for a genetically healthy population to establish). Propagule size however, appears to have had a large influence on the size of the established population. A larger propagule size will also have key genetic benefits for the new population as the more individuals that are translocated, the larger the gene pool. This makes the population less susceptible to genetic drift and inbreeding, and the associated negative effects on species' fitness, extinction risk and evolutionary potential (Miller, 2009; Jamieson and Lacy, 2012).

Comparison between Penned Sites from 2009 and 2012

Penning individuals for a minimum of four months became the recommended penning time for green-gecko translocations after Knox *et al.* (2017) concluded that penning for four versus nine months did not affect post-release dispersal. The resighting rates between the two penned release sites in this study, further support the concept of a time threshold, at which point further penning time is unnecessary. This is evident as the likelihood of resighting an original gecko was not greater at Site 1 (where geckos were penned for three months longer than at Site 3), and a smaller proportion of the propagule size was detected at Site 1 than Site 3. It must be noted however, that the proportion of founders resighted at both sites was relatively low (especially Site 1), therefore only large differences between the sites were detectable. In addition to an effect of habitat complexity, the low sightings (of founders and geckos in general) at Site 1 may also be a reflection of the time since the 2009 translocation. Jewelled geckos are known to live for at least 12 years in the wild (Cree and Hare, 2016a), therefore it is expected that more of the 2012 founders will be alive, than the 2009 founders. The single 2009 founder resighted in this study (in 2020), was originally released as an adult and has therefore lived to at least 14 years old within the ecosanctuary.

Long-Term Dispersal of Translocated Individuals Detected

Other studies have reported the use of food (for the pygmy bluetongue lizard, *Tiliqua adelaidensis*; Ebrahimi and Bull, 2012), life-history stage released (Texas Horned Lizards, *Phrynosoma cornutum*; DeGregorio *et al.,* 2020) and penning (Knox and Monks, 2014; Knox *et al.,* 2017; Flynn-Plummer and Monks, 2021) to reduce post-release dispersal of lizard species following translocation, and encourage establishment at the release sites. My study however, is the second (to Fitzgerald *et al.,* 2015) to report the dispersal distances of founder individuals beyond the initial monitoring period, and the first to analyse dispersal 8-11 years following translocation.

Long-term post-translocation dispersal was reported for the Saint Croiz ground lizard (*Ameiva polops*) following a 10-week penned release (Fitzgerald *et al.*, 2015). Similar to this study, after 5 years, sightings were the greatest near the pen sites, however large dispersal distances were found with most sightings made within 500 m and one individual found ~1,250 m from the release sites. Species' life history (namely the distance travelled per generation and the rate of population growth), may play a role in the dispersal rate expected, as within 5 years, the founder *A. polops* population size had increased 26-fold, which has likely driven the dispersal observed (Fitzgerald *et al.*, 2015; Angeli *et al.*, 2018). These dispersal distances reported (~500 m from the release site) suggest that penning may be a more effective translocation tool for reducing dispersal in species with slow life histories (like green geckos) than others. However, one jewelled gecko born at Site 1, was resighted 2,100 m from its previous location (unpublished data, Cary Knox), therefore such high dispersal rates can be reached by this species. It is impossible however, to determine the maximum dispersal distances travelled by jewelled geckos released within Orokonui, because of the effect low detection rates may have on the patterns observed.

Detectability Challenges Encountered and Recommendations for Future Green Gecko Surveys

The greatest search effort (of ~201-person h over 75 searches) went into Site 3; however, this is an enormous investment of observer time. Furthermore, 95 % of the total geckos sighted at Site 3, were found within the first 36 searches (after 159-person h of searching). This could be used as a guideline for the time investment required to resight ~95 % of green geckos. Such information can be used to better inform future post-translocation monitoring following future green gecko translocations, or the long-term monitoring programs for translocations that have already taken place (e.g., in Flynn-Plummer and Monks, 2021). The time needed will vary however, depending on the release method used, propagule size, the release or pen area and habitat structure and complexity.

It was evident that the sighting per unit effort was significantly greater in winter than in spring and summer. It is likely that during spring and summer, when there are more sunlight hours per day and the sun is higher up in the sky throughout the day, geckos are utilising the tops of the habitat more (which is less visible to observers). Geckos will also be able to bask more efficiently during summer and will therefore be more likely to travel greater distances than they did during winter, potentially into habitat that is inaccessible to observers.

This also highlights the major challenge detecting cryptic species, like many of New Zealand's geckos (that exhibit arboreal and/or nocturnal behaviour), poses for post-translocation monitoring (Van Winkel, 2008; Bell and Herbert, 2017; Towns *et al.*, 2016; Berger-Tal *et al.*, 2019). There is an urgent need for the development of more effective monitoring techniques or abundance models (e.g., Yamaura *et al.*, 2016; Angeli *et al.*, 2018) that reduce the effects of sighting bias associated with surveying green geckos, in particular in tall and dense habitat, where detection of green geckos are the lowest (Knox, 2011).

With the current techniques available, I recommended that future gecko surveys are conducted on sunny days during winter, when geckos are the most detectable. It must also be noted that night-spotting, while an effective surveying technique for green geckos on warm nights (Monks *et al.*, 2017), was not used in this study. I suggest that this technique is adopted in future surveys, especially to assist in the detection of geckos utilising complex and tall habitat.

Conclusions

All three translocations of jewelled geckos to Orokonui Ecosanctuary have reached Stage 2 (evidence of reproduction) of the Miller *et al* (2014) criteria for translocation success. In addition, Stage 3 (population growth) has likely been reached at the 2012 penned and hard release sites, regardless of the release method used. These are the first green gecko translocations conducted between 1994 and 2010 to be successful to the point where population growth is suspected and close to being confirmed. It is too early however, to detect a self-sustaining population (Stage 4) at the release sites. This study also provides strong evidence that jewelled geckos have been moving into new areas of suitable habitat within the ecosanctuary and are establishing new, small populations. Penning (compared to a hard release) appears to have little influence on the likelihood of resighting founders within the release area, as well as the linear dispersal distances travelled by founders, eight years following release. This suggests that the primary benefit of penning is to reduce short-term dispersal and promote population growth at the release site. The propagule size however, appears to be important for the establishment of a large population size, long-term.

CHAPTER 3

The Effects of an Outdoor Enclosure on the Thermal Ecology, Home Range Size and Body Condition of Jewelled Geckos

Introduction

As with mammals and birds, adequate space, mental stimulation and suitable habitat are key requirements for reptile enclosures, to enable and promote natural behaviours and good animal welfare (Benn *et al.,* 2019). Enclosure designs that do not address the captive species' needs can cause discomfort and stress, which has the potential to pose a risk to the animal's survival (Koolhaas *et al.,* 2011; Beenher and Bergman, 2017). Changes in behaviour (in particular increased aggression) and the development of stereotypic (abnormal, repetitive and functionless) behaviour can be used as indicators of stress and poor animal welfare (Mason,1991; Wingfield, 2006; Ward *et al.,* 2018). Such behavioural assessments have been used to highlight the need to provide sufficient enrichment (Bashaw *et al.,* 2016) and space (Warwick *et al.,* 2013) for lizards.

A suitable thermal environment and provision of enough basking opportunities throughout the day is also essential for these ectothermic animals (Fleming *et al.,* 2003; Hawkins and Willemsen, 2004; Besson and Cree, 2011; Doneley *et al.,* 2018). Providing a suitable thermal environment can be challenging for indoor enclosure designs. Numerous factors must be considered, including a thermal and UV light gradient, heat, humidity, photoperiod, vegetation, refuge, basking areas, water quality and presentation, substrate (type and temperatures) and the presence of furniture e.g., branches. One key challenge is that the design must accommodate the particular species' size, behavioural, psychological, thermal, habitat and dietary requirements. In the elements required to address these needs must often be artificially replicated (Hawkins and Willemsen, 2004; Doneley *et al.,* 2018). Air temperatures, basking opportunities, and for some reptiles, soil temperatures must also be regularly monitored in case of a fault. While outdoor enclosures may be exposed to relatively similar light and temperature regimes to wild individuals, several factors must still be considered to ensure a suitable thermal environment is provided. These include the climate suitability, the orientation of enclosure vegetation in relation to the sun, availability of shelter and the height of surrounding vegetation (and the degree of shading this creates for the

enclosure) (Doneley *et al.*, 2018).

Published studies of negative responses observed in captive reptiles focus largely on the effects of overcrowding (Hawkins and Willemsen, 2004; Warwick *et al.*, 2013). While the needs of captive reptiles have been addressed in numerous papers (Burghardt, 2013; Warwick *et al.*, 2013; Bashaw *et al.*, 2016; Benn *et al.*, 2019), none to my knowledge have published experimental findings on enclosure design impacts on the basking behaviour, thermoregulation and social behaviour of the captive species, short or long term. The effect of a suppressed home range on individuals in low density captive populations (where overcrowding is not occurring) is also poorly addressed. Evidence from captive mammals with large home ranges and daily travel distances (Mallapur and Chellam, 2002; Clubb and Mason, 2007) suggests that reptile enclosures that suppress individuals' natural home ranges, may trigger the development of stereotypic behaviour or learned laziness. Furthermore, an increase in the frequency of aggressive interactions may be triggered, especially in species known to be territorial (Stamps and Krishnan, 1998; Hawkins and Willemsen, 2004).

In October 2020, the construction of a jewelled gecko captive breeding enclosure within Orokonui Ecosanctuary was completed. Between December 2020 and January 2021, eight jewelled geckos were sourced from the established populations in the wider ecosanctuary (as described in Chapter 2) and translocated into the enclosure. The purpose of the enclosure is to act as a source for repopulating the wider sanctuary. The enclosure will be stocked with ten geckos, and neonate geckos born within the enclosure will be released into the wider ecosanctuary to promote genetic integration and population growth of the ecosanctuary's already established populations (Figure 3.1; Knox *et al.*, 2019). This enclosure was also designed for public engagement, education and advocacy and aimed to provide visitors with the rare opportunity to observe a jewelled gecko (Appendix 2).

The effects of the enclosure's size, location and thermal environment were of particular interest. Firstly, jewelled geckos are known to occupy a mean home range size (± SE) of $31.1m^2 \pm 7.5m^2$ (measured from resident adult geckos in the Otago Peninsula population; Knox *et al.*, 2017) and can be even larger for male adults ($42.7m^2 \pm 30.2m^2$; Schneyer, 2001). With a vegetated area of 50 m^2 and the initial stocking density of 10 geckos, the enclosure will provide 5 m^2 per gecko. With the home range sizes reported above, and territorial behaviour observed in wild and captive jewelled geckos (Knox, 2011; Joel Knight, Reptile

Keeper at Wellington Zoo, *pers. comm*.; Appendix 1), the enclosure size is expected to force the inhabitants to encounter a larger density of geckos they would naturally encounter and potentially restrict home range size. In addition, the enclosure is located between the Otago skink (*Oligosoma otagense*) and tuatara (*Sphenodon punctatus*) outdoor enclosures, on the grassland area, near the top of the ecosanctuary. The thermal environment the enclosure provides will have no protection from abiotic factors and members of the public will be able to view the geckos in the enclosure up close (approximately 1 m from the edge of enclosure vegetation), between 0930 and 1630 every day.

Key concerns are that the enclosure's surroundings (open grassland rather than dense, *Coprosma* shrubs) and the sudden and potentially high exposure to visitors may disturb the basking behaviour of enclosure geckos. This could result in behavioural changes (in particular the time they spend on essential activities like basking and foraging). The habitat structure (shorter and sparser structure than the vegetation that dominates the gecko's source location) within the enclosure may also provide an unsuitable thermal environment with fewer basking opportunities. Finally, the restrictions on movements and close proximity to conspecifics imposed by the enclosure size, may increase the number of aggressive interactions occurring, especially as new territories are established.

The primary aim of this study was to compare the basking behaviour, movements, habitat use, interactions and body condition of the enclosure geckos with a group of geckos within the wider ecosanctuary (the "free-roaming" geckos) to assess how well the enclosure is promoting natural movements and behaviours. I addressed three key aspects of enclosure design that must be assessed before a captive lizard environment can be considered suitable: the thermal environment provided, the physical environment provided (location, habitat type, complexity and structure) and the effects of the spatial restrictions imposed (including the implications this has on home ranges and social interactions).

I had three main predictions: (1) I predicted that the thermal environment between free-roaming sites and the enclosure would be similar (in terms of the maximum and minimum temperatures reached throughout the day and enabling geckos to reach their known preferred temperatures). Heating and cooling trends however were expected to differ, reflecting the different location within the ecosanctuary each site occupied and therefore the time of day each site received peak sunlight. (2) I predicted that in response to visitors approaching and

circling the enclosure, an initial period of adjustment would be detected in the basking behaviour of enclosure geckos. Geckos were expected to partially expose themselves more often than fully, compared to the incidence of both behaviours seen in the free-roaming geckos during the study period. During this adjustment period, the above changes in basking behaviour over time were expected to be reflected in cooler body temperatures reached during basking immediately following translocation, compared to later on in the study period. In addition, when basking, all developed divaricating shrubs within the enclosure were expected to be used by enclosure geckos (being the preferred jewelled gecko habitat; Knox, 2011). Furthermore, Orokonui staff expected the enclosure to provide sufficient food resources for supplementation to not be required. I therefore predicted that the body condition index (BCI) of all enclosure geckos would increase between measurements (taken when first translocated and in the final week of this study). (3) I predicted that due to the natural restriction the enclosure imposes, enclosure gecko home ranges would be smaller than those of free-roaming geckos and that as a result, the number of interactions (social and aggressive) would be greater within the enclosure compared to those observed in the free-roaming geckos.

Methods

Study Sites and the Enclosure Design

In this chapter, the thermal environment of sites used by free-roaming geckos in the wider ecosanctuary, and the natural movements and behaviours observed in free-roaming geckos, are compared with those observed within Orokonui Ecosanctuary's jewelled gecko enclosure. These comparisons were used to confirm the suitability of the enclosure design. The sites referred to in this chapter are the same release sites that Chapter 2 focused on, where geckos are known to occupy each site: Site 1 contains the 2009 penned release area; Site 2, the 2012 hard release site and the failed 2014 penned site (~230 m from Site 1) and Site 3, the 2012 penned release site. Site 3 is ~181 m from Site 2 and the furthest from Site 1 (~525 m). Mānuka and kānuka trees and dense *Coprosma* shrubs dominate the vegetation at all sites. The habitat structure at Site 1 is much taller than the other sites, with densely grouped kānuka trees ~7 m tall (compared to a maximum height of ~4.5 m at Sites 2 and 3; Figure 2.1). Specific details on the location of gecko sightings and release sites will not be provided to reduce the risk of illegal collection.

The enclosure contains ~50m^2 of suitable jewelled gecko habitat. The majority of the enclosure habitat has been in development for 12 years, namely the *Coprosma* shrubs, poataniwha (*Melicope simplex*), māhoe (*Melicytus ramiflorus*) tussocks (genus *Chionochloa*), the tree fuchsias (*Fuchsia excorticata*) and groundcover, and is therefore well established (Knox *et al.*, 2019). During the construction of the enclosure in 2020, 11 shrubs were added to the enclosure (three *Pittosporum tenuifoliums*, three *Astelia* plants, two red tussocks (*Chionochloa rubra*), four small-leaved *Coprosma* spp., three snow tussocks (genus *Chionochloa*) and one kauri tree (*Agathis australis*). The barrier is made of macrocarpa wood with hard wood support posts surrounding the vegetation. A plastic wall with a metal lip at the top, lines the wooden barrier to prevent geckos climbing out. Six lengths of wire are spaced 13 cm apart above the wooden railing for security reasons (Figure 3.1 B), and a camera and alarm system are installed to prevent illegal poaching attempts. This design is thought to replicate the geckos' natural environment well and is therefore expected to provide enough cover, thermal refugia, food sources and basking opportunities to one day support 10 adult jewelled geckos, and enclosure-born neonates before they are translocated to the wider ecosanctuary (Knox *et al.*, 2019). To my knowledge, this is the first outdoor, open-top and naturalistic green gecko enclosure. (Appendix 1, Table A1).

Figure 3.1. Orokonui Ecosanctuary's open top, un-supplemented, jewelled gecko captive breeding and viewing enclosure, completed in December 2020 (A) and the barrier design used, view from outside the enclosure (B).

Measuring the Release Sites and Enclosure Thermal Environments

Selection of copper models for assessing operative temperatures:

Physical models (typically hollow, sealed copper tubes with a temperature data logger suspended inside) can be used to measure the temperature a basking lizard would reach in the environment of interest, and how these temperatures would vary throughout the day with the environmental variables (known as the operative temperature; Christian *et al.,* 2016). By placing these models in locations where a lizard would be expected to bask, the thermal environment available to that lizard in a defined area can be mapped.

For a copper model to accurately measure operative temperatures, the thermal conductivity, absorptivity and surface area must match the animal of interest (Christian *et al.,* 2016). Several published studies have reported the use of calibrated copper models to measure the operative temperatures of *Woodworthia* species (Gibson *et al.,* 2015; Penniket and Cree, 2015) however, none to my knowledge, have used calibrated copper models for green geckos. For this reason, this study considered two copper model designs to best estimate the operative temperature for jewelled geckos: the dimensions used for *Woodworthia* species (114 mm x 17.5 mm) and a smaller model (80 mm x 18 mm), based on the snout-vent lengths of adult jewelled geckos (see Cree and Hare, 2016). All models were painted an emerald green to match the dorsal colour of most jewelled geckos within Orokonui Ecosanctuary. This also ensured the absorptivity of the geckos was matched (Bakken and Gates, 1975; Dzialowski, 2005; Bakken and Angilletta, 2014). DS1921G-F5 Thermochron iButtons (temperature data loggers) were used to record temperature within the models (± 0.5°C). One data logger was placed inside each large model, suspended in a plastic sheath to keep it securely placed in the middle; the open end was sealed using black electrical tape. To fit inside the small models however, data loggers needed to be modified (to convert the battery to an external attachment to the data logger still suspended inside the model; prototypes constructed by Jo Virens).

There are mixed reports on the effect model size has on the temperatures recorded (from no effect; Shine and Kearney, 2001, to various colours and sizes having a 2–4 °C difference; Bakken and Angilletta, 2014). I expected the smaller models to be a more accurate proxy of core body temperature than the larger model, because the dimensions better reflected the size of jewelled geckos. The smaller model was also of interest because the external wires enabled downloading of data loggers in the field (unlike the larger model). As the data loggers needed to be modified however, it was a more expensive model to work with and data was only able

to be downloaded via external leads, which dangled from the model and would potentially cause a greater disturbance to geckos in the field. To determine whether there were in fact any thermal differences between the two sizes, I compared the temperatures of small (n=4) and large models (n=4) over two days in a single position exposed to the sun. Data loggers (±0.5°C) were programmed to record temperature every minute. A Mann-Whitney-Wilcoxon test conducted in R revealed no significant difference in the mean temperatures recorded by either model design (p = 0.67; Figure 3.2).

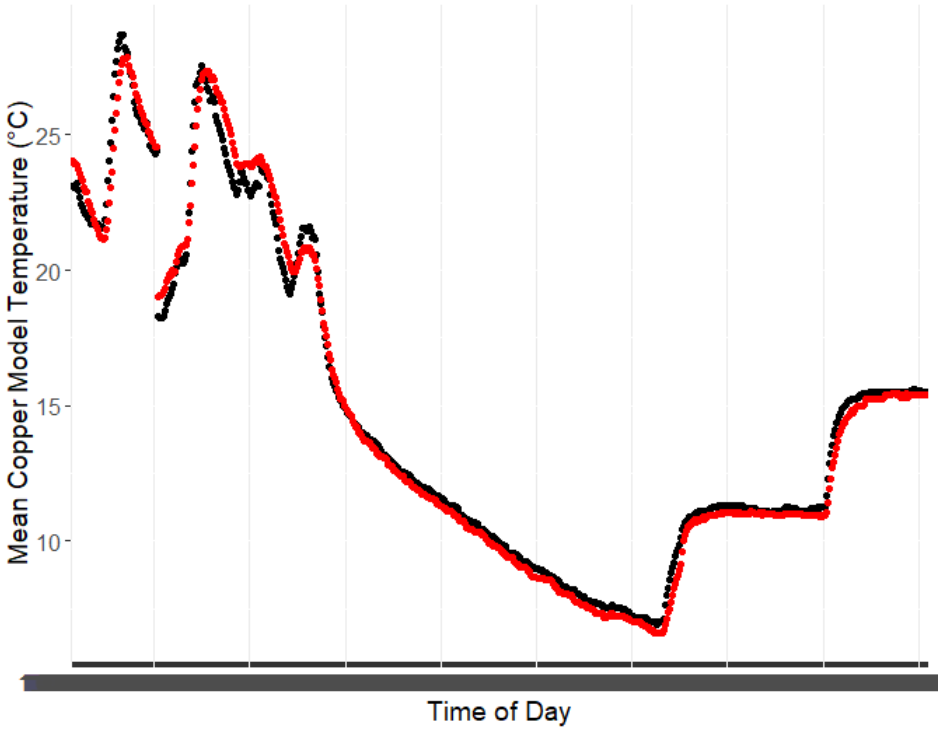


Figure 3.2. The copper model temperature profiles of the smaller jewelled gecko model (n = 4; black line) and larger *Woodworthia* model (n = 4; red line). Temperatures were recorded over two days in June 2020. Temperatures have been averaged per minute across the two days and across models. The Mann-Whitney Wilcoxon test was not significant (p = 0.67).

Calibration of Copper Models Against Live Jewelled Geckos

To truly match the absorptivity of the species of interest, copper models were calibrated against live jewelled geckos over two trials, conducted over eight days. As there was no significant difference between mean temperature recorded and model size (Figure 3.2), both small and large model designs were used in the calibration to maximise the number of locations models could be placed within the tank. I compared model temperatures against

those of three adult jewelled geckos in a 0.62 m^3 indoor glass tank. The tank contained several plants and other structures (ledges, wires) on which the geckos routinely basked. In the first trial (from 1000 NZST 17 June 2020 until 2000 NZST 18 June 2020), four large and four small copper models were placed throughout the tank in locations previously used for basking. In the second trial (1000 NZST 22 June 2020 to 0600 NZST 25 June 2020), I used ten copper models, seven large and three small. The additional models were placed in spots the geckos were predicted to bask in. Models were secured with cable ties where necessary, to attach models to vegetation. Data loggers were programmed to record temperature (± 0.5°C) every 1 minute for trial 1 (so gecko body temperatures were able to be compared to the copper model temperature with ≤1 minute accuracy) and every 2 minutes for trial 2 (to extend the trial time).

Copper model temperatures recorded were compared with the skin surface temperatures of a live gecko basking within at least 2 cm of the model. A thermal image of the gecko was taken using a FLIR i60 handheld thermal imaging camera (FLIR Systems Inc. USA). Thermal images were analysed in FLIR Tools® (https://www.flir.com.au/products/flir-tools/), a skin body temperature was taken from the dorsal posterior abdomen of the geckos (confirmed in *Woodworthia* as a suitable proxy for core body temperature measured with a thermocouple in the cloaca; Chukwuka *et al.,* 2019). Each image was adjusted for air temperature, humidity and distance from the gecko at the time each thermal image was taken and the emissivity was set at 0.95 (Tattersall, 2016). The linear regression analysis reported a strong relationship between gecko skin temperature and copper model temperature at the time the thermal image was taken (adjusted R-squared value of 0.93).

Comparison of Thermal Environments between sites at Orokonui

Based on the outcome of the calibration test above and their greater convenience, I decided to use the large copper models for field measurements. Models were placed during two time periods, the first was considered as "spring" (from 23 October 2020 – 7 December 2021) and the second was conducted in summer (3 January 2021 – 8 February 2021). At the start of the study I intended to only use Site 3 (the 2012 penned release site) as the source for the free-roaming geckos, therefore in spring, copper models were placed throughout Site 3 (n = 18) and the enclosure (n = 10) only. Models were placed in locations jewelled geckos had been observed basking in (at Site 3), and in locations where geckos were expected to bask (in the enclosure, which was still under construction at this stage). To make the position of the

models as comparable as possible, eight of the ten models in the enclosure matched the height, orientation (horizontal or vertical) and compass angle of models positioned throughout Site 3. The remaining two models were placed at different angles and heights to ensure copper models were evenly spread throughout the enclosure, and accounted for the shorter stature of habitat available. Models at the release sites ranged in height from 0.45 m to 2.5 m and 0.43 m and 2.1 m in the enclosure.

In summer, I placed six models throughout the enclosure and Sites 1 and 2, and seven models throughout Site 3. Copper models were established at each release site and the enclosure at different times, but all models were in place by 3 January 2021 and removed on 8 February 2021. To ensure the thermal environments were comparable, only the temperature data collected between 3 January 2021 and 8 February 2021 was analysed in this chapter. The height, orientation and angle of copper models at each site replicated that of at least four of the six copper models in the enclosure. This was to ensure that the thermal environments measured were not only relatively comparable but also reflected the basking environments available and in use by geckos at each site.

Visual Searches for Free-Roaming and Enclosure Geckos

From 15 December 2020 to 7 February 2021, all sites and the enclosure were visually searched for geckos on sunny days when geckos were expected to be basking, as described in Chapter 2. Searches were conducted throughout this period to continue the survey of the populations at each release site, to locate neonates and subadults suitable for translocation to the enclosure and to locate subadults to attach transmitters to (to form the "free-roaming" comparison group of geckos). The order of sites surveyed alternated with each visit to eliminate any temporal bias in the data collection process. Individuals were not marked but were photographed using a Canon 800D camera and a Tamron 18-400 mm lens and identified using their unique natural patterns on the dorsal surface (Knox *et al.*, 2013). The life history stage of each gecko sighted was visually determined (by relative size) as a neonate/juvenile, subadult or adult. When possible, a photo of the lower region of the body was taken to determine the presence (male) or absence (female) of a hemipenal sac. Neonates, juveniles and young subadults were unable to be sexed. As most geckos were not handled, the reproductive state of females was unable to be confirmed via palpation. Instead, photos were analysed by myself and Alison Cree; females that looked potentially pregnant to both of us were categorised as "probably reproductive." This category accommodates any females who

appeared pregnant due to large vitellogenic follicles or early pregnancy (which were thought to be difficult to distinguish without palpation).

Assessing Basking Behaviour in Free-Roaming and Enclosure Geckos

Thermal images were taken ≥0.2 m from free-roaming geckos and ≥0.3 m from enclosure geckos (often restricted by the enclosure barrier as all thermal images were taken outside of the enclosure) to measure the skin surface temperature geckos were reaching during basking. The method for measuring skin temperatures was the same as during the copper model calibration described above. At the time of each sighting, the cloud cover was rated between 0 (no cloud cover) and 8 (complete cloud cover) and wind speed (km/h) was measured using a hand-held anemometer (UT363BT Bluetooth mini anemometer from Hvactools). If a thermal image was taken, the distance from the gecko was recorded. Shade air temperature (°C) and relative humidity at the time each thermal image was taken, were obtained from the Orokonui weather station records (https://fireweather.niwa.co.nz/site/Otago-Dunedin%20-%20Mobile). The vegetation on which each gecko was basking and the type of behaviour observed (partial or full exposure) were also recorded. Behaviours were recorded as either fully basking, partially basking, fully visible or partially visible (visible when the sun was not out or cloud cover was high enough that geckos could not be considered to be basking in the sun). If individuals were resighted more than once during ≥1 h apart, then another thermal image was taken.

Body condition index

Body condition indices (BCI) are used as a proxy of energy reserves (Bonnet and Naulleau, 1994). BCI was estimated as the log transformed mass to log transformed snout vent length (SVL) (as in Hoare *et al.*, 2006). Prior to release into the enclosure all eight geckos translocated were weighed to the nearest 0.01g using a Kern EMB 600-2 electronic balance, and measured to the nearest 1mm (snout-vent length and vent-tail length) In the final week of fieldwork, seven of the eight enclosure geckos were caught and remeasured. Three neonates sighted throughout the sanctuary during searches were also weighed and measured when first sighted. Only one neonate was able to be recaught in the final week of fieldwork for the second round of measurements. The same measurements were taken before a transmitter was attached and once it was removed.

Home Ranges

The GPS location of each gecko's location when first sighted was recorded with at least 5 m accuracy on a GARMIN GPSmap 60CSx using the New Zealand Transverse Mercator (NZTM) coordinate system. At first, the GPS location was taken for every sighting however, this proved to be an inaccurate way of recording small movements. From 19 August 2020, movements were recorded using Knox and Monks' (2014) method. Each gecko location was marked with a peg. The next time that gecko was seen, the distance and compass bearing between its last and current position were taken and the peg was moved to its new location. As the location of each sighting had been recorded, the previous movements of geckos were remeasured using this new method.

Transmitters were used to track the movements of geckos throughout the ecosanctuary to increase the resighting rate of individuals. Five 0.43g BD2N transmitters and five 0.35g BD2X transmitters (Holohil Systems, Carp, ON, Canada) were attached to 10 jewelled geckos (one subadult, four adult females and six adult males) between 29 December and 20 January to monitor their movements for 2-3 weeks. Transmitters were attached the day a suitable individual was sighted and caught. While the batteries in these transmitters typically last three weeks, the period of time the transmitter was attached for was dependent on when it was activated, as these transmitters use a small amount of power at all times and if stored for more than three weeks, the original lifespan is reduced. Transmitters were stored in a refrigerator prior to attachment to reduce the battery drainage. Transmitters weighed <3-7% of geckos' body weight and were attached using an external 'backpack' harness (as used in Salmon, 2002 and Knox and Monks, 2014) using a hypoallergenic, self-adhesive fabric strip (approximately 22cm x 3mm) coloured green with a POSCA water-based, xylene-free pen for camouflage (See Appendix 3, Figures A.3.1. A-B). Geckos were tracked on four to five days a week during all weather conditions (except for rain) and were sighted at least every three days. If one gecko had been tracked for 30 min without successfully sighting the individual, the visual search of the main site was resumed or the next individual in that area was tracked. If the individual had not been sighted in the last two days and the triangulated area did not suggest the individual had moved since the last movement recorded, then tracking continued until the individual or transmitter was located.

Statistical Analyses

Comparing the Thermal Environments at Sites 1, 2, 3 and the Enclosure

The set point temperature range (the central 50% of selected body temperatures in the laboratory; Christian *et al.*, 2016) for jewelled geckos is 25 °C to 28 °C, based on body temperatures of captive bred adult jewelled geckos (n = 10, three non-pregnant females and seven males; Besson and Cree, 2011). Temperatures recorded at 1500 in that study were used, as that was the only time of day when all individuals were basking. To determine if the thermal environment of release sites and the enclosure were similar, the proportion of mean hourly temperatures during spring (between Site 3 and the enclosure) and summer (between Sites 1, 2, 3 and the enclosure) during the sunlight hours (0500 – 2000 NZDT), were categorised as either within the set point temperature range or not. A generalised linear mixed model with a binomial family was used. This tested the relationship between the proportion of temperatures per hour for each model, each day that were within the set point temperature range (the response variable) and the season (spring and summer, only Site 3 and the enclosure had copper model data from both seasons) site (Sites 1, 2, 3 and the enclosure; fixed factors) and the interaction between the two. Copper model was included as a random factor. The statistical model was checked for collinearity by calculating the variance inflation factors (VIF values; all values were <2) and overdispersion (1.8). To account for a small amount of overdispersion (>1), an observation-level random effect was added to the model.

Comparison of Basking Behaviour between Free-Roaming and Enclosure Geckos

To assess whether the basking behaviour (in terms of skin temperatures reached and frequency of full basking, as opposed to partial basking) between free-roaming and enclosure geckos were statistically different, I intended to run a linear mixed model and a generalised linear mixed model (with a binomial family and logit link). The first was to analyse the relationship between gecko skin temperature (the response variable, normally distributed and used a proxy for core body temperature; Chukwuka *et al.*, 2019) and group (enclosure or free-roaming), sex (male, female or unconfirmed for juveniles and neonates/juveniles), age (adult, subadult or neonate/juvenile), season (spring or summer) and air temperature (continuous predictor) at the time the thermal image was taken (the fixed variables), using Gecko ID as a random variable. The second was to test the relationship between the frequency of full exposure (as opposed to partial exposure; the response variable) and the group, time of day, air temperature and cloud cover when each observation was made (predictor variables) with Gecko ID as a random variable. For analyses on basking behaviour

observed, the basking and visible categories were combined as full or partial exposure. Both models encountered singularity that could not be resolved through simplifying the models; therefore, gecko ID was incorporated into two linear models and two multi-factor ANOVAs run. Residual plots were checked for outliers.

Effect of Adjustment Period on the Basking Behaviour of Enclosure Geckos

Due to singularity issues, linear mixed models were unable to run. Instead, to test whether an adjustment period was detected in the basking behaviour: (1) the proportion of partial versus fully basking and (2) the skin temperatures reached by enclosure geckos' overtime, linear and generalised linear models were used. The linear model tested the relationship between enclosure gecko skin temperature (the response variable, normally distributed), and the air temperature at the time the thermal image was taken, as well as the number of days the gecko had been in the enclosure for (the predictor variables). The generalised linear model tested the relationship between the frequency of full basking (response variable, binomial family, logit link) and the time of day, air temperature, cloud cover and days since release into the enclosure (predictor variables). Gecko ID was incorporated into the two linear models as the third and fifth predictor variables and a multi-factor ANOVA run. Model checking involved checking residual plots for outliers.

Differences in Perch Heights Used by Free-Roaming and Enclosure Geckos

This analysis excluded data of individuals that were tracked to ensure perch heights used by free-roaming geckos were comparable with those used by enclosure geckos (only sighted). Perch heights were normalised through a log transformation. The relationship between perch height and site (Site 1, 2, 3 or the enclosure), age of geckos and the season the observation was made in were tested using a linear mixed model with gecko ID as a random variable. The model was checked for collinearity (all VIF values were <3) and residual plots checked for outliers.

Changes in Body Condition Observed in Enclosure Geckos

To account for each gecko having paired BCI measurements (two BCI each, when first released into the enclosure and within the last week of the study), a paired t-test was run to compare the BCI for enclosure geckos when first released into the enclosure and in the final week of the study (days between measurements ranged from 9 to 49). Normality of the differences of the pairs was checked using a Shapiro-Wilk normality test.

Free-Roaming and Enclosure Gecko Movements (Using Sighting and Telemetry Data)
The distance and degrees data collected during the study were converted to GPS locations using the first GPS location recorded. New Zealand Transverse Mercator coordinates were converted to UTM coordinates and 95 % minimum convex polygons (MCP; mcp function; ‘‘adehabitatHR’’ package; Calenge, 2006) were estimated for individuals with at least five location points (from either sighting or telemetry data; data from the two collection methods were not combined to estimate MCPs). Home ranges observed in separate seasons were calculated separately. Surveys were sparse in spring and few sightings were made in summer therefore movements recorded in these two seasons were combined as the “warmer months”. MCPs between the life history stages (adults, subadults and neonates) and the sex of individuals (males and females) were analysed separately to maximise sample sizes analysed (as all neonates and unidentified subadults were removed when analysing the relationship between MCPs and sex of individuals). MCPs were not able to be calculated for 14 individuals (eight adults, three subadults and three neonates) as they were observed < five times.

To determine whether 95 % MCPs (m^2) of free-roaming geckos differed between life history stages and sex (to better understand the natural movements of free-roaming geckos), a linear mixed model was used. The distribution of 95 % MCPs could not be normalised through transformations. Life history stage and sex were analysed separately with the season the last location point was collected in (winter or warmer months) and number of observations used to calculate the MCP (the fixed variables), using Gecko ID as a random variable. The original data (for life history stage analysis) and log transformed data (for the sex analysis) were analysed as they best resembled a normal distribution. For both analyses, the residuals were normally distributed. The statistical model was then checked for collinearity (all VIF values were <3.2 and <2.6) and residual plots checked for outliers.

To determine if 95 % MCP area was different in the life history stage and sex (fixed variables) of geckos tracked, 95% MCP area from the telemetry data (response variable) were normalised through a log10 transformation and analysed in a linear model. The days each individual was tracked for (which ranged from 9 to 20 days) was also included. One male was removed from this analysis as it was only tracked for 3 days. The model was checked for collinearity (all values were <2) and residual plots checked. Unfortunately, the same analysis but for 95 % MCP area estimated for enclosure geckos, was unable to be tested due to small

sample size. Instead, means and standard error are presented in the results.

To incorporate the movement data recorded for geckos who were sighted on less than five occasions (and therefore an MCP could not be estimated), the distance travelled between the first two sightings of every gecko sighted was calculated. New Zealand Transverse Mercator coordinates were converted to decimal degrees and the geodist function (Padgham and Sumner, 2020) was used to estimate the distance (m) between the first two locations for each gecko. The distances travelled were compared between the life history stages (adults, subadults and neonates) and the sex of individuals (males and females) in separate analyses. The distance between locations (the response variable) was normalised through fourth root transformations, and two linear models were carried out to test the relationship between the distance travelled and the sex (or life history stage) of the individual and the number of days between observations (the fixed variables). The model was checked for collinearity (all VIF values were <1) and residual plots checked for outliers.

Results

Comparing the Thermal Environments at Sites 1, 2, 3 and the Enclosure

The mean daily minimum and maximum copper model temperatures reached during summer, varied among the three release sites and the enclosure (Figure 3.3). The mean daily maximum model temperatures (± SE) at Site 1 (24.9 °C ± 1.4), Site 2 (22.1 °C ± 1.2) and Site 3 (23.6 °C ± 1.3) were reached at 1200 or 1300. Mean temperatures were cooler and peaked later on in the day in the enclosure (20.6 °C ± 1.1) at 1500. The mean daily minimum temperatures were reached at 0400 at all four sites (ranging from 9.2 °C; Site 1, to 9.7 °C within the enclosure).

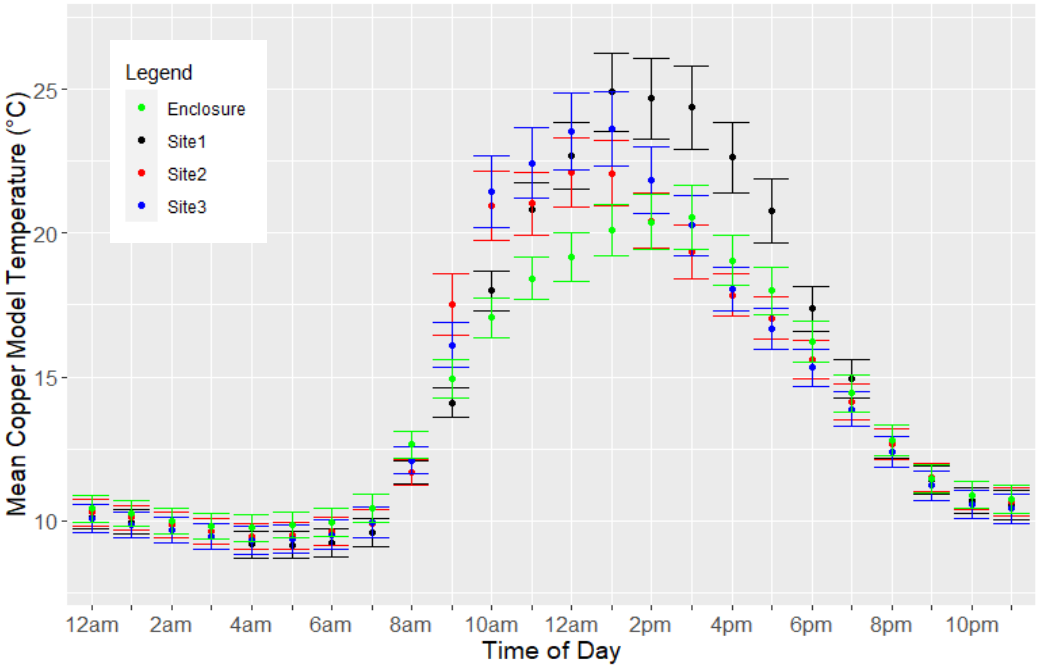


Figure 3.3. Mean average operative temperatures recorded hourly from 3 January – 8 February 2021 (*n* = 36 days) at the 2009 penned (Site 1), 2012 hard (Site 2) and 2012 penned (Site 3) jewelled gecko release sites within Orokonui Ecosanctuary and the new outdoor jewelled gecko enclosure (at ~302 m, 322 m, 354 m and 320 m elevation). Recorded over summer from 3 January to 8 February 2021. Temperatures were first averaged across models and then hours of the day. Error bars represent standard error.

Operative temperatures (the temperature a basking lizard would reach if in the same position; Christian *et al.*, 2016), measured by copper models, were within and at times exceeded the jewelled gecko set point temperature range (25 °C to 28 °C) at each site (Figures 3.4 A-D). The GLMM identified non-significant trends for the percentage of hours models were within the set point range between sites and season (with the largest percentage of hours within the set point range found at Site 1 and during summer; Table 3.1; Figure 3.5).

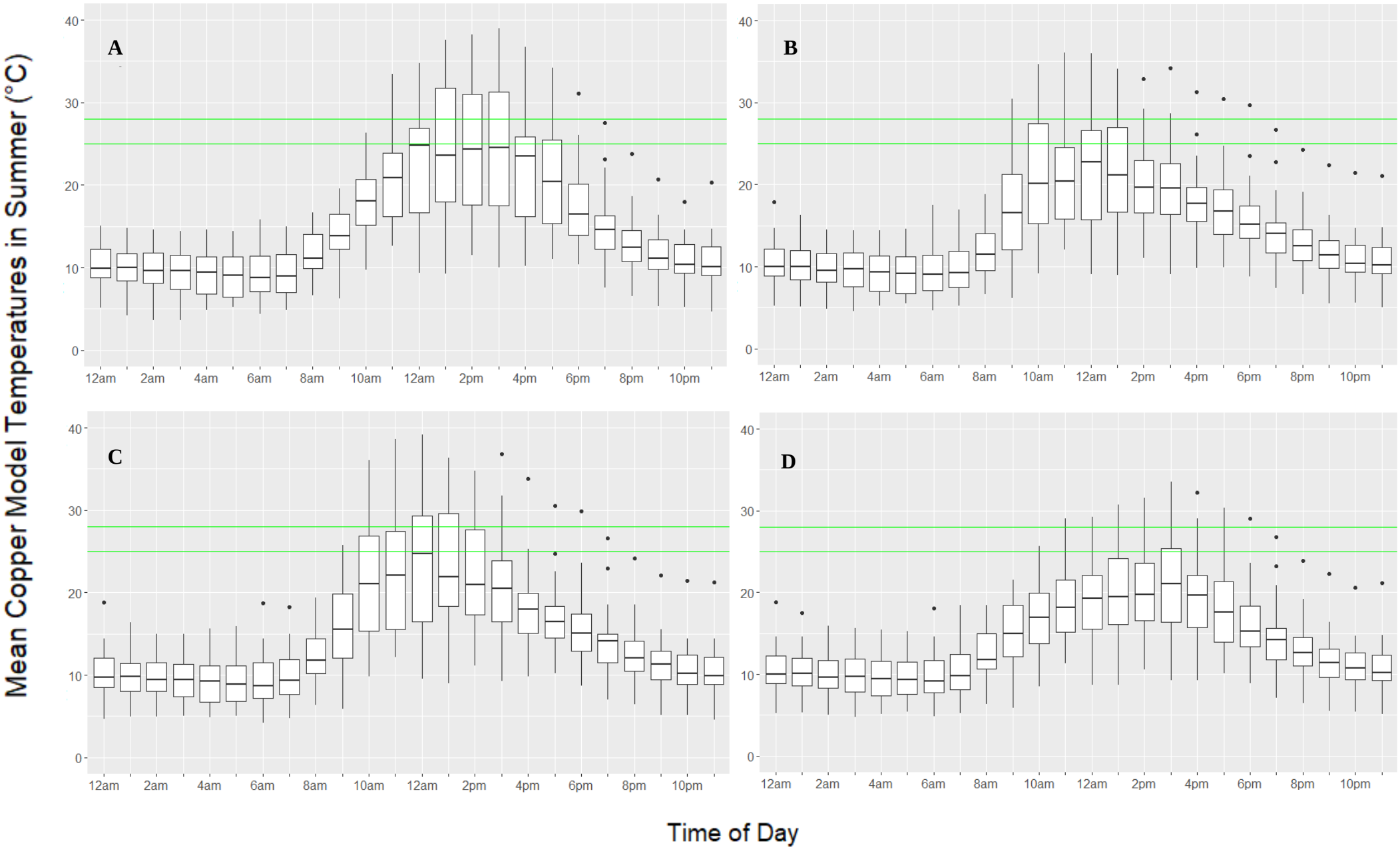


Figure 3.4. The spread of hourly mean copper model temperatures during Summer (3 January 2021 to 8 February 2021) at Site 1 (A), Site 2 (B), Site 3 (C) and the enclosure (D). Temperatures were recorded over summer from 3 January to 8 February 2021. The green lines represent the known set point temperature range for jewelled geckos (25 °C to 28 °C; taken from Besson and Cree, 2011). All outliers are included.

Table 3.1. The output of the generalised linear mixed model analysis on the percentage of hours within the known jewelled geckos set point temperature range (25 °C to 28 °C; taken from Besson and Cree, 2011) between the season (spring and summer) and site (Sites 1 = 2009 penned release, Site 2 – 2012 hard release, Site 3 = 2012 penned release site, Enclosure = Orokonui Ecosanctuary's new outdoor jewelled gecko enclosure. Percentage of hours are based on the jewelled gecko operative temperatures (the temperature a basking lizard would reach in the environment of interest), recorded on temperature data loggers placed inside calibrated copper models. Sample sizes vary between seasons and sites because of the number of copper models used. *More hours have been recorded at Site 3 and within the enclosure (compared to Sites 1 and 2), because they were the only thermal environments measured in spring. The analysis revealed no significant differences.

	Variable	Number of copper model temperatures (and copper models)	Mean hours within the set point range	Standard Error	Degrees of Freedom	Wald Test Statistic	P value
Season	Spring	16240 (28)	3.2	0.17	1	2.88	0.09
	Summer	13370 (24)	4.8	0.23			
Site	1	3480 (6)	6.0	0.51	3	6.70	0.08
	2	2900 (5)	4.6	0.50			
	3	14134 (7*)	4.5	0.37			
	Enclosure	9096 (6*)	4.3	0.27			

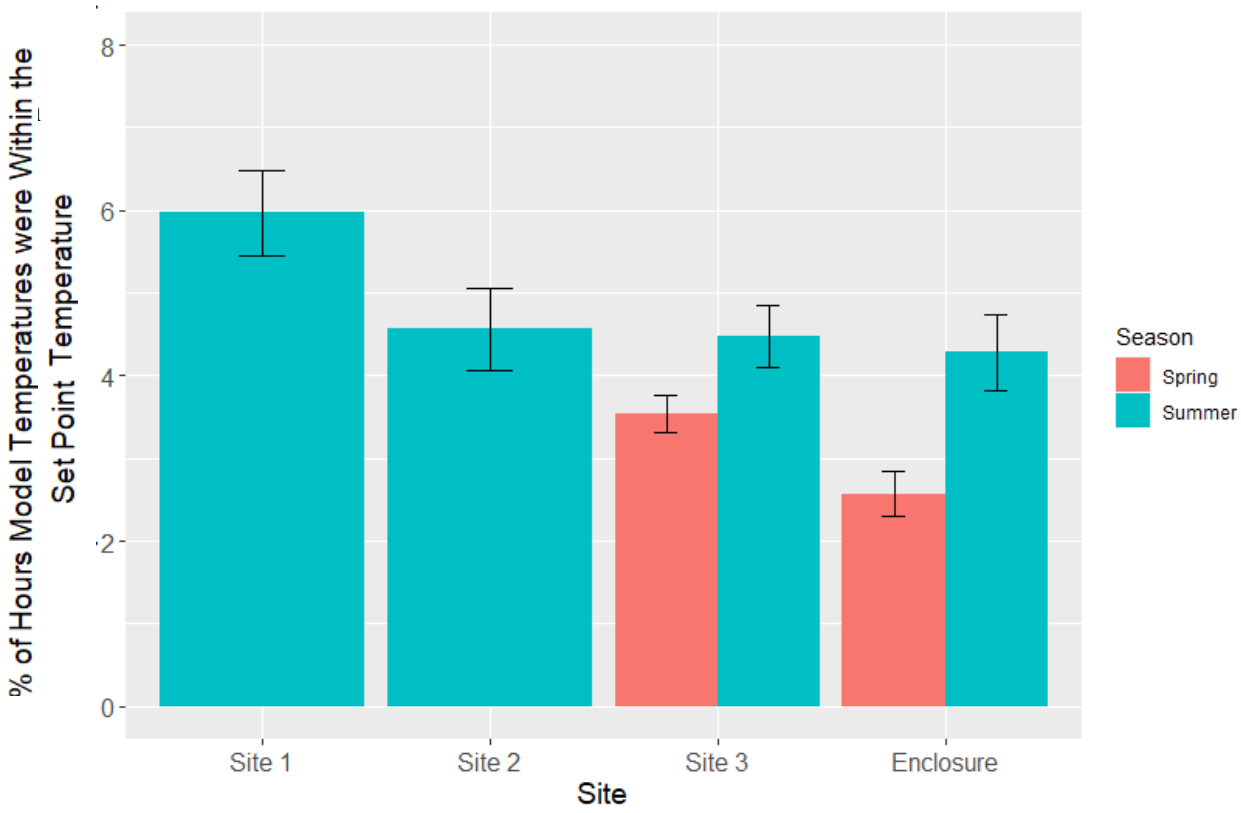


Figure 3.5. The percentage of hours copper model temperatures (calibrated for jewelled geckos) were within the set point temperature range (25 °C to 28 °C; taken from Besson and Cree, 2011) during sunlight hours (0500 to 2000) at the jewelled gecko 2009 penned (Site 1), 2012 hard release (Site 2) and 2012 penned release (Site 3) sites within Orokonui Ecosanctuary, and the Ecosanctuary's new outdoor jewelled gecko enclosure, during Spring (23 October 2020 to 30 November 2020) and Summer (3 January 2021 to 8 February 2021). Error bars represent standard error.

The Thermal Ecology of Free-Roaming and Enclosure Geckos

In terms of gecko skin temperatures, 17 % of the temperatures reached by geckos at Site 1 were above the selected temperature range, 13 % were within the range and 70 % were below it (Figure 3.6 A). Similarly, at Site 3: 18 % were above the range, 12 % within the range and 70 % below (Figure 3.6 B). By contrast, 15 % of enclosure gecko skin temperatures were above the set point range, 24 % within and 61 % below (Figure 3.6 C). The greatest body temperature reached by a gecko basking in summer was 32.3 ^{o}C by a neonate at Site 1, and the lowest temperature reached was 12 ^{o}C by a subadult in the enclosure. The linear mixed model revealed sex, age, group (enclosure versus free-roaming geckos), season and gecko ID to have no significant effect on the gecko body temperatures reached (Table 3.2). Air temperature at the time of the thermal image was the only significant predictor (Table 3.2), with air temperature having a positive relationship with gecko temperature.

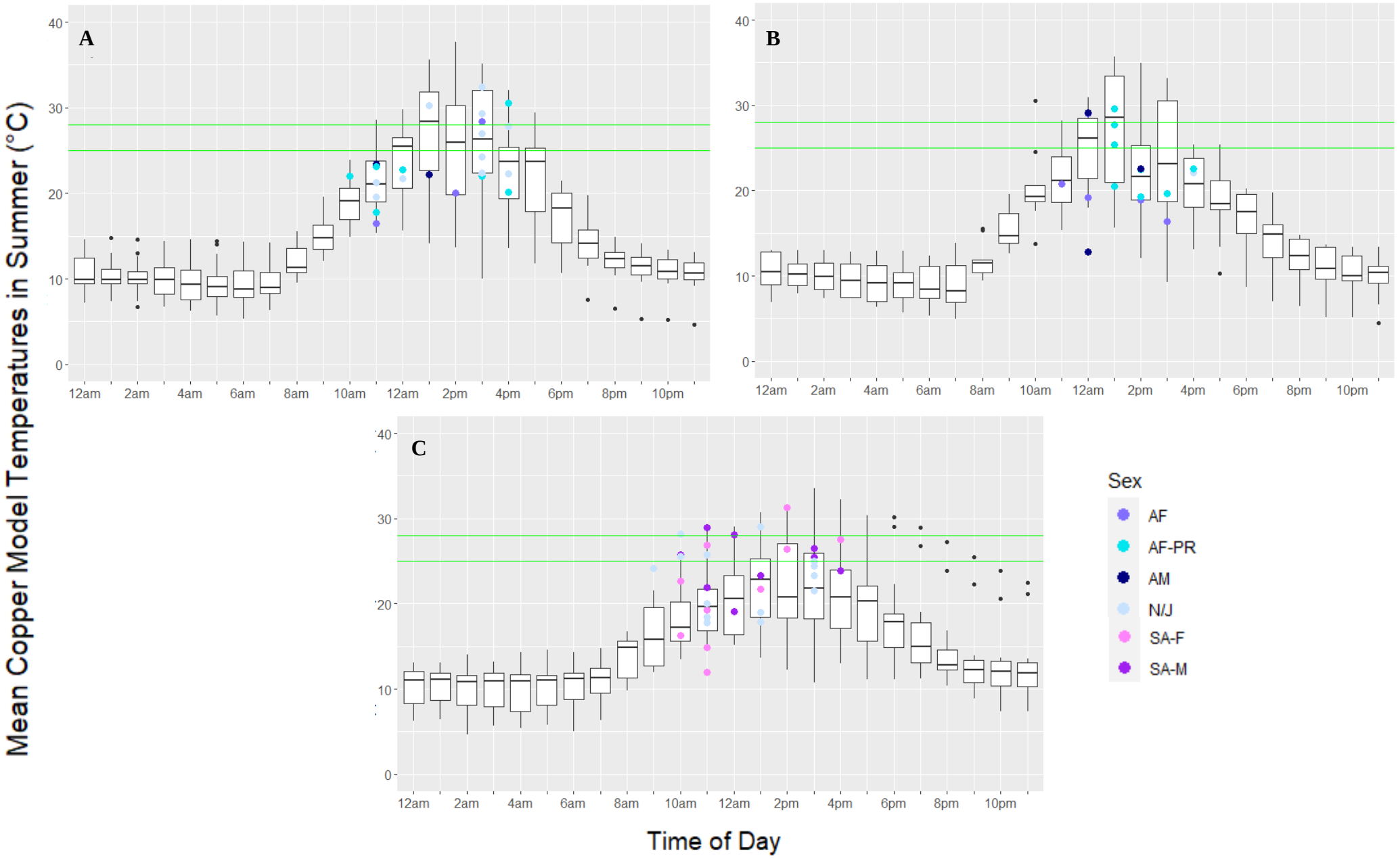


Figure 3.6. The spread of mean daily copper model temperatures on days when thermal images were taken at Site 1 (A), Site 3 (B) and the enclosure (D). The green lines represent the known set point temperature range for jewelled geckos (25 °C to 28 °C; taken from Besson and Cree, 2011). Operative temperatures were recorded using calibrated copper models over summer from 3 January to 8 February 2021. Dots represent a gecko body temperature and are coloured according to the sex and life history stage of individuals. Each body temperature does not represent a new individual. Site 1 *n* = 6 geckos, Site 3 *n* = 13 geckos, enclosure *n* = 8 Geckos. No outliers were identified.

Table 3.2. The full output of the linear mixed model testing the relationships between gecko skin temperature and the sex and life history stage of the gecko, whether the individual was a free-roaming or enclosure gecko and the season and air temperature at the time thermal image was taken. Sample sizes for the levels of each factor are provided. **F** = female, **M** = male, **A** = adult, **UC** = Status is unconfirmed due to poor photo quality, **A-PR** = female adult, probably reproductive, **N** = neonate/juvenile, **SA** = subadult, **E** = enclosure gecko, **FR** = free-roaming gecko. * indicates a significant p value (<0.05).

Predictor Variable	Gecko Sample Size (87 observations)	Degrees of Freedom	F Statistic	Effect Size	P value
Sex (31 UC)	39 F 17M	2	1.6	<0.01	0.20
Life History Stage	17 A 19 A-PR 20 SA 31 N	2	2.8	<0.01	0.07
Group (Free-roaming versus enclosure gecko)	35 E 52 FR	1	0.3	<0.01	0.62
Season	12 Spring 75 Summer	1	0.8	<0.01	0.36
Air Temperature	87	1	6.3	0.10	0.02*
Gecko	87 (24 geckos)	20	0.7	0.20	0.78

Detecting an Adjustment Period in the Basking Behaviour of Enclosure Geckos

The linear model revealed was no significant relationship between enclosure gecko skin temperature and day since release (df = 1, F = 1.6, p = 0.21; Figure 3.7). There was a non-significant trend between skin temperature reached and air temperature (df = 1, F = 3.6, p = 0.07, small partial eta squared value = 0.13), with air temperature having a positive relationship with gecko temperature.

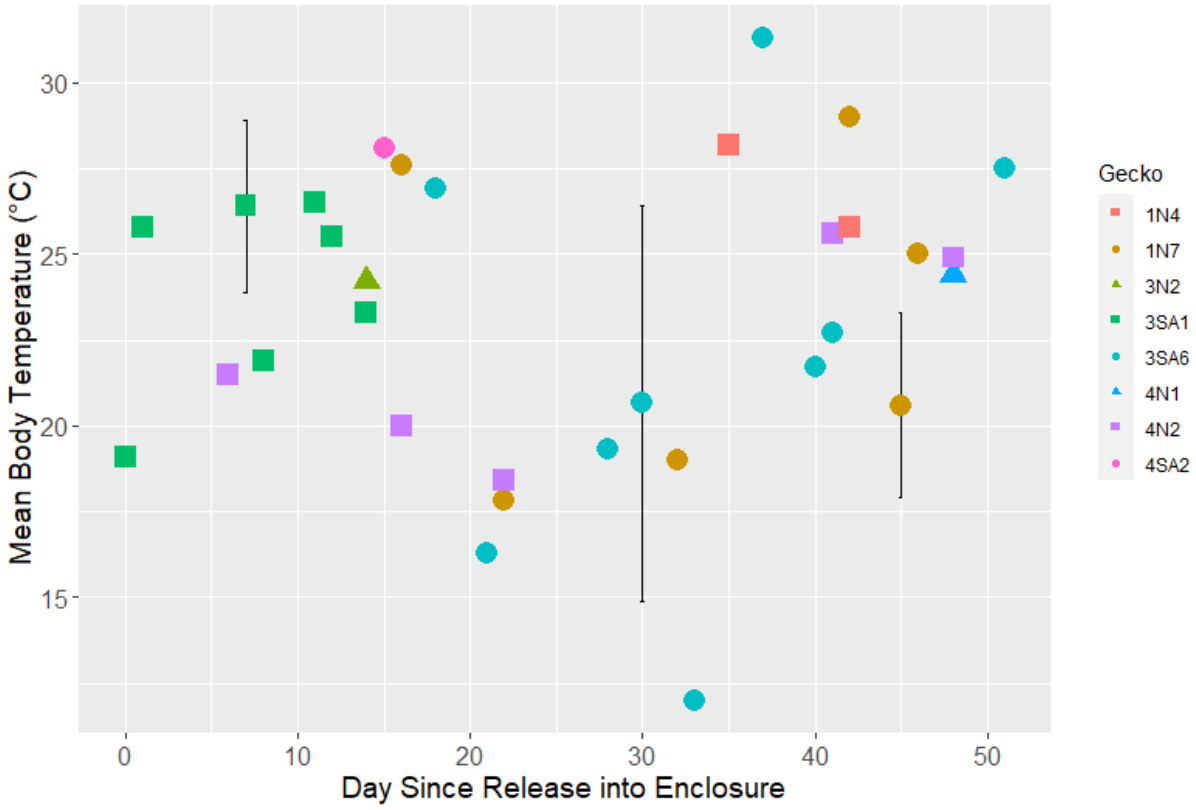


Figure 3.7. The skin temperature of jewelled geckos (within Orokonui Ecosanctuary's outdoor jewelled gecko enclosure) over time since release within the enclosure (0 to 51 days). Each point represents an individual geckos' skin temperature (°C). If individuals were resighted during a visual search, at least 1 h later, another thermal image was taken. For these individuals, the mean skin temperature reached that day ±SE is plotted. Geckos were released into the enclosure on five different occasions between 22 December 2020 and 7 February 2021.

Cloud cover had a significant positive effect on the degree of exposure seen when visible or basking (fully versus partially) in both free-roaming and enclosure geckos (df = 1, p = 0.03). There was no effect of time since release on the likelihood of enclosure geckos fully exposing

themselves (df = 1, p = 0.50). It should be noted however, that detectability of individual enclosure geckos varied. Throughout the study, each gecko was sighted on average six times following release (ranging from only 1 to 15 resightings). In addition, the time between the first sighting following release varied among individuals. It took an average of 17 days to resight an individual however this ranged from 1 to 48 days.

Differences in Perch Heights and Habitat Used by Free-Roaming and Enclosure Geckos

Free-roaming geckos used significantly higher perch heights (1.9 m ±0.06 m) than the enclosure geckos (1.13 m ±0.04 m; df = 1, Wald test statistic = 8.0, p = 0.008). This was reflected in the perch heights used by the subadult tracked prior to translocation, with an average perch height (based on sighting data) of 1.2 m in the enclosure (±0.1 m) but an average of 2.3 m (±0.4 m) in the wider ecosanctuary. When tracked this individual's perch height used increased to 5 m. In addition, of the free-roaming geckos, adults were sighted significantly higher (2.2 m ± 0.08 m) than subadult (1.5 m ± 0.1 m) and neonates/juveniles (1.3 m ±0.1 m) (df = 2, Wald test statistic = 12.3, p = 0.004).

Geckos observed basking on habitat edges and tracked throughout the wider ecosanctuary were sighted on 11 different plant species or on the ground, and tracked through rank grass (Table 3.3). *Coprosma* species were among the top four most commonly used plant species (*C. dumosa* used in 38% of the observations by 43 geckos, *C. propinqua* in 15.1% by 12 geckos and unidentified *Coprosma* species used in 6.9% observations by 9 geckos). Mānuka was the second most common species used (in 20.9% of observations by 27 geckos). The only plant species used by the ecosanctuary jewelled geckos that were present inside the enclosure were *C. dumosa* and *C. propinqua*. No enclosure geckos were observed to use the *C. dumosa* within the enclosure and only one individual was observed basking on *C. propinqua* (Table 3.4). Instead, *C. rugosa* was the most commonly used plant species (used in 56% of the observations) and the only plant used by more than three geckos in the enclosure (used by seven of the eight geckos within the enclosure; Table 3.4). Additional divaricating shrubs that were not observed to be used within the enclosure were poataniwha (*Melicope simplex*) and māhoe (*Melicytus ramiflorus*). Interestingly, a copper model was placed on both the poataniwha and māhoe in anticipation of them being popular basking spots. The operative temperatures recorded on these shrubs were the warmest mean temperatures from 11am to 2pm within the enclosure by 5-6 ^{o}C (Figure 3.8).

Table 3.3. A summary of the plant species free-roaming jewelled geckos were observed on in the Orokonui Ecosanctuary between 14 June 2020 and 7 February 2021. Plant species are ordered from most to least frequently used.

Plant Species Used by Jewelled Geckos in the Wider Ecosanctuary	**Present in the Enclosure?**	**Percentage of Sightings**	**Number of Free-Roaming Geckos Observed Using the Species**
Coprosma dumosa	Yes	38%	43
Mānuka	No	20.9%	27
Miki (*Coprosma propinqua*)	Yes	15.1%	12
Unidentified *Coprosma* spp.	-	6.9%	9
Pohuehue and Round leaved coprosma (*Coprosma rotundifolia*)	No	3.8%	2
Kohuhu (*Pittosporum tenuifolium*)	No	3.6%	10
Rank grass	No	3.3%	5
Pohuehue (*Muelhlenbeckia australis*)	No	2.3%	7
New Zealand Broadleaf (*Griselinia littoralis*)	No	1.3%	3
Hupiro (*Coprosma foetidissima*)	No	0.8%	1
Kotukutuku (*Fuchsia excorticata*)	Yes	0.3%	1
Three Finger (*Pseudopanax colensoi var. ternatus*)	No	0.3%	1
Tauhinu (*Ozothamnus leptophyllus*)	No	0.3%	1
Ground	-	0.3%	1

Table 3.4. A summary of what plant species within Orokonui Ecosanctuary's jewelled gecko enclosure were observed to be used by jewelled geckos between release within the enclosure (between 16 December 2020 and 25 January 2021) to 6 February 2021.

Plant Species Present	Used by Enclosure Geckos?	Percentage of Sightings on	Number of Geckos Observed Using the Species
Coprosma rugosa	Yes	56%	7
Korokio (*Corokia cotoneaster*)	Yes	23%	3
Miki (*Coprosma propinqua*)	Yes	9%	1
Snow Tussock Grass (*Chionochloa rigida subsp. rigida*)	Yes	6%	2
Mikimiki (*Coprosma crassifolia*)	Yes	4%	2
Kotukutuku (*Fuchsia excorticata*)	Yes	2%	1
Poataniwha (*Melicope simplex*)	No	0%	0
Māhoe (Genus *Melicytus ramiflorus*)	No	0%	0
Coprosma dumosa	No	0%	0

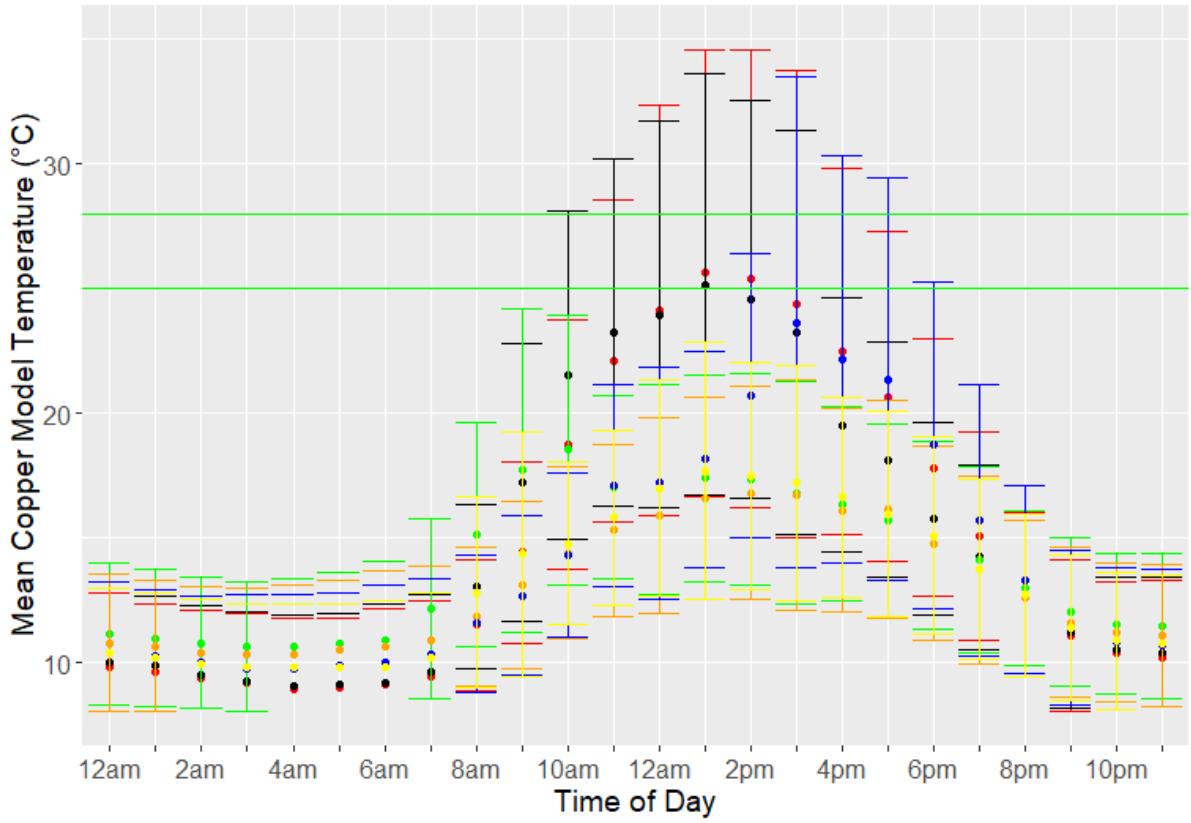


Figure 3.8. The mean hourly operative temperatures recorded by the six models placed throughout Orokonui Ecosanctuary's outdoor jewelled gecko enclosure. The green lines represent the known set point temperature range for jewelled geckos (25 °C to 28 °C; taken from Besson and Cree, 2011). Temperatures were recorded over summer from 3 January 2021 to 8 February 2021.The black and red trends represent the two copper models that were placed on the poataniwha and māhoe, which contrary to prediction, no enclosure geckos were observed using.

Changes in Body Condition Observed in Enclosure Geckos

Seven of the eight enclosure geckos were recaptured in the final week of the study for a second BCI to be estimated. The average number of days between the two measurements was 36 days but ranged from 9 to 49 days. Five of the seven enclosure geckos reweighed showed an increase in body condition index between the first and last measurements (including all neonates remeasured; Figure 3.9). One subadult (3SA1) showed a small decrease in BCI (of 0.01). The paired t-test showed that the BCI of the enclosure geckos was significantly higher by the end of the study (compared to when first released); df = 7, t statistic = -0.07, p = 0.01).

One free-roaming neonate (1N5, of three neonates) was recaptured at the end of the study (43 days following the first measurements) to represent the free-roaming neonates. This individual had a lower BCI than all enclosure geckos for both measurements. The average difference in BCI of enclosure neonates from the start to the end of the observation period, was 0.04 (ranging from a 0.01 decrease, after 9 days within the enclosure, to a 0.08 increase, after 48 days in the enclosure). The free-roaming neonate's BCI increased by 0.06. Due to the small sample size however, statistical analysis was unable to be run to determine if there was a significant difference between free-roaming and enclosure gecko changes in BCI. Comparisons will be influenced in any natural fluctuations in body weight, for example, one gecko's weight decreased by 0.5g following defecation during processing.

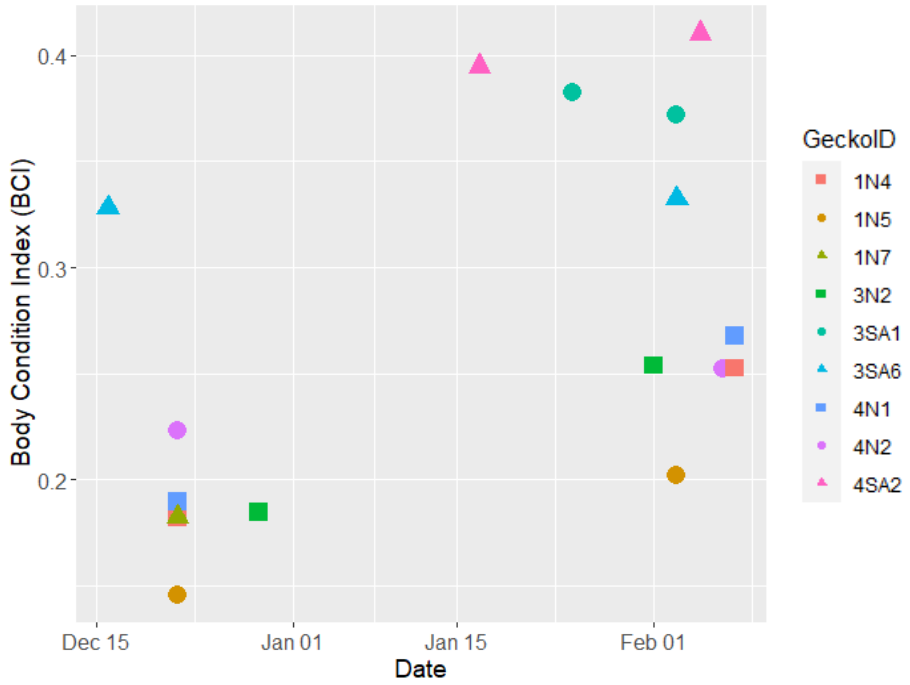


Figure 3.9. The body condition index (BCI) of each individual gecko within the enclosure (five neonates and three subadults) and one free-roaming neonate (1N5) when first translocated to the enclosure (or first sighted for the free-roaming individual), and in the last week of the study (1 – 7 February 2021). BCI significantly increased by the end of the study (paired t-test, $p = 0.01$).

Free-Roaming and Enclosure Gecko Movements (Using Sighting and Telemetry Data)

Free-Roaming Gecko Movements Observed

There appeared to be a trend between 95 % MCP area (m^2) and life history stage, with adults occupying larger home ranges than subadults and neonates/juveniles (Table 3.4; Figure 3.10), however the linear mixed model reported this trend (n = 13 adults, 4 subadults and 4 neonates/juveniles, df = 2, Wald test statistic = 4.3, p = 0.12) and the relationship between MCP area and sex to not be statistically significant (df = 1, Wald test statistic = 0.02, p = 0.88). Variation in adult 95% MCP area was large in adults but small in both subadults and neonates/juveniles (Table 3.4; Figure 3.10). Season was not a significant predictor for 95% MCP area in either of the life history stage or sex analyses (linear mixed model, df = 1, Wald test statistic = 0.88, p = 0.88) despite the appearance of a trend with a larger average MCP area in the warmer months than during winter (Table 3.4). Linear models revealed adults travelled significantly further between the first two sightings than subadults and neonates/juveniles (Table 3.4; df = 2, F = 13.2, p = <0.001) but sex was not a significant predictor of distance travelled (df = 1, F = 2.1, p = 0.17). The number of observations had a significant positive influence on the 95% MCP area estimated (df = 1, p = <0.03) for both analyses. Whereas, days between observations, was not a significant predictor for distance travelled for either analysis (df = 1, p = 0.33 and 0.22).

Tracked Gecko Movements

During the study, 10 free-roaming jewelled geckos (four adult females, five adult males and one subadult male) were tracked throughout Orokonui ecosanctuary for an average of 16 days (ranging from 5 to 20 days). There was a range of success in transmitter attachment. Two geckos were able to be tracked for 16-19 days with no attachment issues. The tape started to unravel on four geckos, who were recaught and retaped. One of these individuals then needed the transmitter reattached five days later. Reattachment was required if the individual was sighted with the transmitter hanging off or the transmitter had fallen off and the individual was resighted. An additional two geckos required reattachments 3-10 days following initial attachment. One of these geckos lost its transmitter six days following reattachment and an additional two transmitters were found unattached. Attachment difficulties appeared to be more frequent in more active individuals (*pers. obs.*). In addition, six of the seven geckos remeasured following transmitter removal exhibited a decrease in weight (on average -0.17 g ± 0.19 SE).

Table 3.5. Summary of the mean and standard error values for the 95% minimum convex polygon area (MCP) and distanced travelled between the first two sightings for life history stage, sex and season. 95% MCPs were calculated for each individual gecko sighted at least five times between 10 July and 7 January, and the distance travelled between the first two sightings was calculated for every gecko sighted twice in winter (10 July – 29 August 2020). Separate analyses were run for the effect of life history stage and sex on 95% MCPs and distances travelled. This was to maximise the sample size for life history stage analyses as neonates/juveniles and some subadults were unable to be sexed. Differences in sample sizes are included. The only significant effect was life history stage on 95% MCP area (linear mixed model, p = <0.001).

Predictor Variable	Number of Gecko 95 % MCP Areas	Mean 95 % MCP Area	Standard Error of 95 % MCP Area	Number of Geckos Distances	Mean Distances	Standard Error Distances
Sex	3 F	32.8	20.5	7	1.9	0.4
	2 M	13.5	5.6	9	4.2	1.3
Life History	5 A	24.1*	9.9	14	3.5	0.9
Stage*	1 SA	1.3	1.1	4	0.8	0.4
	2 N/J	0.3	0.2	4	0.04	0.04
Season	11 Winter	7.2	3.5	NA	NA	NA
	10 Warmer Months	24.0	13.1	NA	NA	NA

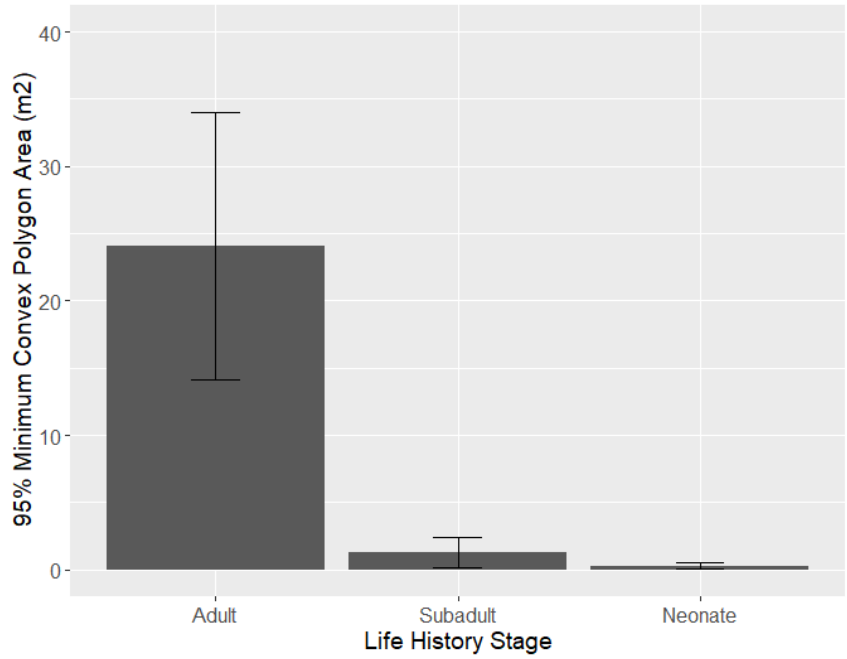


Figure 3.10. The 95% Minimum Convex Polygon area (m^2) estimated for free-roaming adult, subadult and neonate/juvenile jewelled geckos. Location points were collected over 74 visual searches throughout Orokonui Ecosanctuary conducted between 4 July 2020 and 7 February 2021.

The effects of transmitter attachment on the degree of skin sloughing and gecko skin condition also varied on removal (16 – 20 days following attachment). One transmitter was shed off entirely after ten days (but the individual was resighted and the transmitter reattached). Another gecko's skin was severely sloughing beneath where the transmitter had been attached and a third gecko had begun to slough its skin where the tape passed over the gecko's right arm to wrap beneath the chest (Appendix 3, Figure A.3.1: E-F). Of the remaining five geckos that were able to be recaught to manually remove the transmitter, four of them (including the individual whose transmitter was reattached following a full shed), showed varied levels of discolouration (duller skin colour), often seen on geckos prior to skin sloughing (for example, Appendix 3, Figure A.3.1. C-D).

Most geckos were tracked to trees, bushes and shrubs however, four geckos were tracked through the grass. One male adult was located in the grass for nine consecutive days before the transmitter was removed. This relationship between sex and 95% MCP area of tracked geckos was almost significant (df = 1, F statistic = 7.5, p = 0.05) with males occupying larger mean MCP areas than females (Figure 3.11).

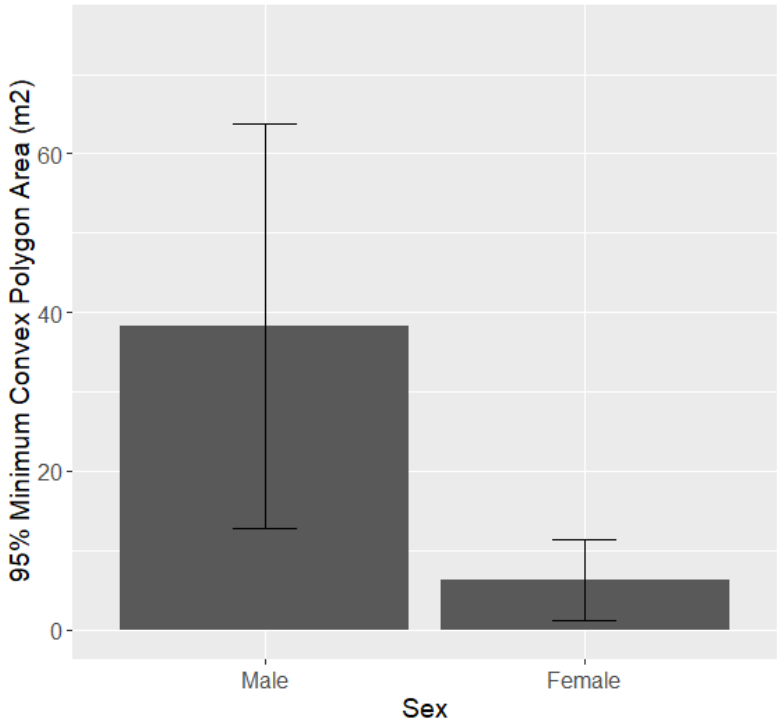


Figure 3.11. The 95% Minimum Convex Polygon areas (m^2) estimated for free-roaming adult (n=9 geckos: 4 adult females, 4 adult males and 1 subadults) jewelled geckos tracked for 9 to 20 days between 29 December 2020 and 5 February 2021. One male was removed from this analysis as it was only tracked for 3 days.

Enclosure Gecko Movements

There was a large amount of overlap in home ranges between the geckos within the enclosure (Figure 3.12) however no aggressive interactions were observed. The size of the home ranges based on movements observed however, varied between individuals. The mean 95% MCP area of neonates/juveniles was 0.9 m^2 (ranging from 0 m^2 to 2.4 m^2 ±0.8 m^2 SE) and appeared to be smaller than the mean MCP area for subadults (14.2 m^2 ± 6.6 m^2 SE), although this could not be statistically confirmed because of the small sample sizes (n = three subadults and three neonates/juveniles). The 95% MCP area of the single neonate regularly sighted within the wider ecosanctuary was 0.18 m^2. Gecko 4SA2 was tracked for 19 days prior to release into the enclosure. The 95% MCP area was estimated to be 15.4 m^2 when free to roam within the wider ecosanctuary (with ten location points following tracking), however was estimated to be 12.6 m^2 based on observed movements over 19 days (and five location points observed) within the enclosure.

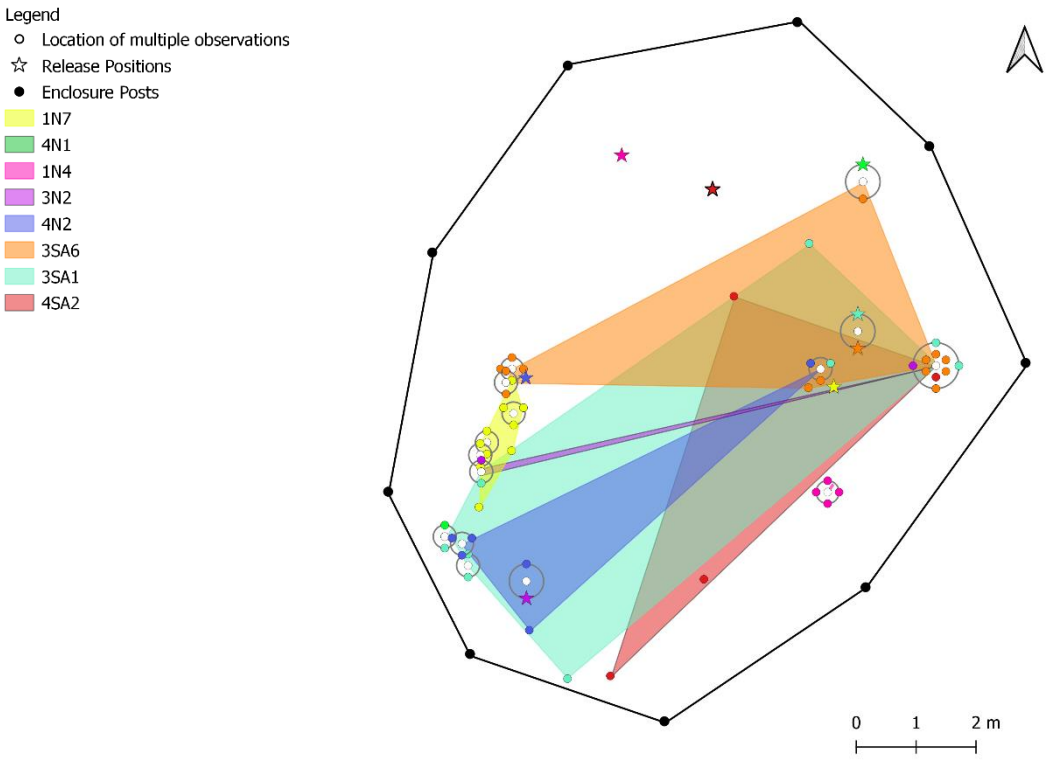


Figure 3.12. The 100% minimum convex polygons (MCPs) for each jewelled gecko inside the Enclosure based on movements observed since release to the enclosure (between 16 December 2020 and 25 January 2021) to 7 February 2021. Areas do not include the release position, therefore only represent the area selected by geckos. Dots represent an individual observation and are colour coded according to the identity of the individual.

Discussion

The copper model temperatures reached at each site and within the enclosure varied throughout summer, with warmer mean temperatures recorded at Sites 1 and 2 and cooler temperatures at Site 3 and the coolest temperatures within the enclosure. However, the proportion of hours model operative temperatures were within the jewelled gecko set point temperature range, was very similar between Site 2, Site 3 and the enclosure. Furthermore, the set point temperatures were reached by jewelled geckos at all four sites. Gecko sightings were concentrated in the South-west corner of the enclosure and contrary to prediction, geckos did not bask on all divaricating shrubs available. Below I further discuss the suitability of the enclosure thermal environment and enclosure size in terms of promoting natural behaviours, that were observed in the free-roaming geckos in the wider ecosanctuary. I then make some recommendations for the enclosure design and future monitoring of the translocated population.

The Enclosure Thermal Environment and Thermal Ecology Observed in Enclosure Geckos

The differences between the value and timing of maximum operative temperatures at Sites 1, 2, 3 and the enclosure can likely be attributed to the difference in site location and elevation. Variation in site elevation and aspect would influence the time of day the sun reached each site, and the surrounding vegetation may have different shading effects. For instance, the area surrounding the enclosure is exposed to open grassland and therefore may be more influenced by abiotic factors than other sites with dense and tall surrounding vegetation. There was also a small variation in copper model placement and orientation between sites (with up to two of the six copper models at each site having a unique height, orientation and degree to the sun). This was to ensure the thermal environment measured was representative of the environment being used and the height of vegetation available to resident geckos, which differed slightly at each of the three release sites.

There was a trend for the proportion of hours model temperatures were within the set point temperature range of jewelled geckos (25 °C to 28 °C; Besson and Cree, 2011), to vary between sites, with a greater percentage of hours at Site 1. Thus, while the mean daily operative temperatures within the enclosure during summer were slightly cooler than those at Sites 1, 2 and 3, the enclosure provided geckos with the same opportunities to reach their set point temperature. Free-roaming and enclosure geckos reached the same skin temperatures

and the greatest proportion of these gecko skin temperatures within the set point range, was reached by enclosure geckos. This suggests that geckos were able to bask and achieve the same body temperatures in both environments and that the enclosure provides a suitable thermal environment for the geckos. While air temperature influenced gecko skin temperature reached, it is unlikely that the days thermal images were taken influenced this result as all sites were surveyed on days suitable for basking.

Time since release had no effect on the skin temperatures reached by enclosure geckos or the frequency of full and partial exposure (when basking or visible). This lack of an effect suggests that an adjustment period was not detected in enclosure geckos' basking behaviour. One explanation for this result is that visitors searching for and observing the geckos within the enclosure were not disturbing geckos to the point where their basking behaviour was affected. Although gecko basking behaviour did not change over the time since the release (within the period observed), it does not mean that geckos are unable to be disturbed by loud or large groups of visitors. A few individuals within the enclosure were observed to retreat when approached by visitors. This was not interpreted as unusual behaviour however, as a few individuals spotted in the wider ecosanctuary also retreated at times, especially if they had been basking on a hot day (*pers. obs.*). Observing individuals retreating reinforces the naturalistic nature of the enclosure and how natural behaviour is promoted. It also reinforces the fact that there is still a need to promote and encourage respectful behaviour when approaching and walking around the enclosure.

The time taken to resight each individual following release, and the total number of times each individual was sighted during the study, varied among individuals released into the enclosure. This suggests that individual detectability varies, with some individuals taking longer to become visible basking at the edges of vegetation (fully expose themselves) following release. This is potentially because they are adjusting to the new environment or establishing territories. An adjustment period could be inferred from this sighting frequency data if the point was reached where all enclosure geckos were being sighted regularly however, one individual was only able to be resighted on the final day of the study (48 days following release). Basking habitat selected may also have contributed to the differences in individual gecko sighting rates. While all habitat within the enclosure was searched during each visual survey, gecko detectability on the fuchsia trees was expected to be much lower than if a gecko was basking on a *Coprosma* bush, for example (*pers. obs*.). It is not possible

to distinguish the effects the translocation itself and the basking habitat selected had on the individual detectability of enclosure geckos.

Habitat Use Within the Enclosure

Contrary to prediction, not all of the suitable habitat within the enclosure was used for basking. There were no sightings of geckos on the divaricating shrubs: poataniwha (*Melicope simplex*), māhoe (*Melicytus ramiflorus*) or *Coprosma dumosa*. The lack of use of the *Coprosma dumosa* plant on the south side of the enclosure, can likely be attributed to the shading the south side of the enclosure received as it was located behind the two tree fuchsias (the tallest plants within the enclosure). Therefore, other vegetation within the enclosure likely provided more suitable basking positions. It was surprising that no individuals were seen on the poataniwha or māhoe, both being divaricating species and in direct sunlight for most of the day. In fact, two of the copper models were placed on both of these shrubs, which confirmed them to be highly suitable basking habitat as these two models had the two warmest mean temperatures from 11am to 2pm by 5-6 ^{o}C. This suggests that enclosure geckos are not utilising some of the ideal basking locations the enclosure provides or that it is unsuitable.

It could be that the thermal environments on these shrubs were too hot (reaching temperatures above 30 ^{o}C). Although I would expect it to still be used, as jewelled geckos retreat into the vegetation when it gets too warm. Or, jewelled geckos may not favour these plant species (as free-roaming geckos were not observed using these species either, but this was likely due to the low availability of these species in the wider ecosanctuary). A few jewelled gecko sightings have been made on *Melicope simplex* in the Otago Peninsula population though; Knox, 2011. It may also represent a height preference, with the māhoe being <0.45 m tall. While four free-roaming geckos were observed basking at a height <0.5 m, the average perch height was 1.9 m and those basking at <0.5 m, were utilising a well-developed and densely vegetated shrub or tree, at least 2m tall (unlike the māhoe plants in the enclosure. Perch height preferences have been reported in other arboreal lizard species (e.g. 18-22 m in *Tropidurus azureus werner*; Ellinger *et al.,* 2001; and 1/10 tree height in arboreal desert lizards; Vitt *et al.,* 1981), but not in green geckos. The perch height enclosure geckos are able to occupy also appears to be restricted by the statue of vegetation within the enclosure, with the majority reaching between 1-2 m tall (as opposed to ~4.5 m to ~7 m at Sites 1, 2 and 3).

There is also a self-introduced population of New Zealand grass skinks (*Oligosoma polychroma*) within the enclosure. Grass skinks are commonly seen basking on these low plants and the surrounding rocks and may therefore be driving jewelled geckos away from using such suitable basking habitat. In addition, insects are primary components of both the grass skink and jewelled gecko diets (Spencer *et al.*, 1998; Jewell and McQueen, 2007; Knox, 2011). Therefore, the presence of a grass skink population within the enclosure holds the potential for competition for food to arise, especially considering the enclosure prevents migration to the wider ecosanctuary for both lizards. It is expected that if intra or inter-specific competition for resources was occurring, that this would be reflected in the body condition index of at least some enclosure geckos. Fortunately, a significant increase in body condition index (BCI) was detected. This result suggests that the enclosure was able to support at least eight jewelled geckos without resulting in a loss of condition over a 2-month period. The only decline in BCI (of 0.01) recorded was due to a decrease in weight of 0.03 g, which could be attributed to defecation prior to collection and is therefore not of concern.

Assessing the Suitability of the Enclosure Size

Aggression, overcrowding and declines in body condition over time can be indications that an enclosure is not providing enough space or resources for the density of animals contained within (Stamps and Krishan, 1998; Hawkins and Willemsen, 2004; Warwick *et al.*, 2013). Between release in the Orokonui enclosure (from 16 December 2020 onwards) until the end of this study (7 February 2021), there were no sightings of aggressive behaviour. This result suggests that the enclosure was able to support at least eight jewelled geckos without inducing aggressive interactions over a 2-month period. It is also apparent, that observations were clustered in the north-east, west and south-west ends of the enclosure, with the north section of the enclosure largely unused. It is suspected that these patterns are driven by the suitable thermal environments these popular sites provide geckos, and the gap in habitat and potentially unfavourable plant species or height structure present in the north section (*Melicope simplex* and *Melicytus ramiflorus*).

For free-roaming geckos, movements (the distance between the first two sightings) were significantly larger for adult jewelled geckos than subadults and neonates/juveniles. In addition, from the tracking data, males appeared to have larger 95% MCPs compared to females. Males have been reported to occupy larger MCPs than females in other jewelled

gecko studies, (Schneyer, 2001, Knox *et al.*, 2017), which has been attributed to the search for potential mates (whereas female home ranges are thought to be solely resource dependent (Rose, 1982; Schneyer, 2001). This is the first green gecko study however to report a significant relationship between life history stage and movements, with juveniles moving smaller distances and a trend for smaller home ranges in younger individuals. Significantly larger adult home ranges have been observed in other lizard species too (e.g. the sleepy lizard, *Tiliqua rugosa*; Bull and Baghurst, 1997 and Mona Island iguana, *Cyclura cornuta stejnegeri*; Pérez-Buitrago and Sabat, 2007).

Based on the significant findings in this study and those reported above from other studies, it is likely that jewelled gecko home range size increases with age and are significantly larger for males. However, a range of different methods to derive movement data were used in my study (tracking versus sighting, MCPs versus movements between consecutive locations), and they did yield contrasting results. The most likely limitation in detecting consistent results across these analyses was the small samples in some of these datasets. In the 95% MCPs based on sighting data, only six adults, two subadults and two neonates followed by two males and three females could be included. Similarly for the 95% MCP areas based on radio tracking data, eight adults but only one subadult could be included. These low sample sizes are a result of the low detectability of this cryptic species, especially in summer (as discussed in Chapter 2) and the limitations radio tracking imposes on the size of geckos able to be tracked. In contrast, the dataset comprised of distances between the first two sightings for each gecko resighted was relatively large (n=7 females, 9 males, 14 adults, 4 subadults and 4 neonates/juveniles), yet I could not detect an effect of sex on movement distances. This suggests that a long-term measure (with >2 observations) is required to detect differences in movements between female and male jewelled geckos.

In general, these patterns described from my study, in addition to other published studies reporting larger home range sizes in males (Schneyer, 2001), suggest that home ranges and movements differ between life history stage and sex, and that these are innate and natural behaviours. It is possible that as the individuals within the enclosure age, they may naturally start to look for more space, in particular adult males. While no evidence of territorial or aggressive behaviour was recorded in this study, reports of aggressive and territorial behaviour (often by males) in captive green geckos (including captive jewelled geckos) during the breeding season (Appendix 1), suggest that there is the potential for issues

surrounding the enclosure stocking density to be encountered in the future.

Skin Sloughing with Holohil BD2N (0.43g) and BD2X (0.35g) Transmitters

It has been suggested before that there may be an association between transmitter attachment and triggering geckos to slough their skin (Schneyer, 2001). In my study, sloughed skin was observed in three geckos. In addition, five geckos showed varied levels of skin abrasion seen as skin discolouration (Appendix 1, Figure A.1.1) following transmitter removal. A duller skin colour is often seen on geckos prior to skin sloughing. Stronger evidence for this association is the fact that one individual shed its transmitter after nine days of attachment and then signs of skin abrasion beneath the transmitter were observed nine days following the second attachment. These observations suggest that transmitter attachment (of even 0.35 g and 0.43 g transmitters) for 16 to 21 days can cause gecko skin abrasion and trigger individuals to slough their skin. Furthermore, six of the seven geckos remeasured following transmitter removal exhibited a decrease in weight (between 0.04 – 0.87g). It is difficult to determine the cause however, as weight of an individual will naturally fluctuate and be influenced by defecation prior to collection (which in this study was found to have as large an influence on gecko weight as 0.5g).

Management Recommendations for the Enclosure Population

It is recommended that the grass skink population is monitored to ensure that they do not outcompete the jewelled geckos for food resources in the future. Evidence of resource and habitat conflict between the two species could include declines in enclosure gecko body condition indices, if an extreme abundance of grass skinks were counted or any concerning interactions between the two species observed. Artificial cover objects and pitfall trapping are commonly adopted monitoring techniques for skinks including *O. polychroma* (Lettink *et al.*, 2011; Dent, 2016). I suggest either technique is used within the enclosure at routine intervals each year to quantify the abundance of grass skinks present and inform future management decisions. Pitfall trapping may be of greater use as it would enable easy removal of grass skinks if there were concerns. It may also be of interest to the ecosanctuary to remove all grass skinks to see if that encourages geckos to bask on the poataniwha and māhoe plants (which would make for easier sighting opportunities for visitors too).

There is a small gap in the ground cover of the north facing side of the enclosure behind one of the māhoe plants. This has been confirmed to contain some of the warmest basking habitat

within the enclosure (based on operative temperatures recorded on one of the mahoe plants), but is currently not being used. There are several small *Coprosma* spp. that have been planted here and will fill the gap in the future however, due to the short stature and sparse foliage of these young bushes, it is likely that the geckos will continue to utilise other more developed habitat for the foreseeable future. It is therefore recommended that a large, at least 2m tall (based off the mean perch height of 1.9m used by free-roaming geckos), well developed *Coprosma* spp. (*C. dumosa* or another *C. propinqua*) or mānuka shrub is planted here to give the geckos more opportunities to utilise this side of the enclosure for basking. Maximising the number of basking spots and opportunities within the enclosure will be most beneficial during winter as the time taken for jewelled geckos to digest food is known to significantly increase as temperature decreases from 20ºC to 5ºC (although digestion was still possible at 5ºC, unlike for tuatara and McCann's skinks; Besson and Cree, 2011). As this study focused on the thermal environment over spring and summer, the suitability of the environment and the operative temperatures geckos could reach during the coldest months at Orokonui Ecosanctuary, are unknown.

This study focused on the movements, behaviour and body condition index of individuals when there were eight individuals within the enclosure, but the final two geckos have since been translocated into the enclosure. Attempting to provide more basking opportunities in the north side of the enclosure may reduce the potential for overcrowding by encouraging greater use of the enclosure habitat and therefore potentially reduce the risk of territorial behaviour. This is of interest as the final two geckos settle in and will likely be important in the future, when geckos begin to reproduce. The final recommendation is to continue monitoring the body condition index and inter-specific behaviour of the enclosure geckos at least twice a year to ensure the suitability of the enclosure long-term, especially as geckos age, start to reproduce and now that the density of geckos has increased to ten individuals. Of particular interest, is to ensure there is not an abundance of males present (which may drive territorial and aggressive behaviour between individuals). Six of the neonates/juveniles were unable to be sexed. It is therefore essential to identify the sex ratio of the translocated population.

Conclusions

The enclosure is providing geckos with the same opportunities to reach their set point temperature than sites used by free-roaming geckos, and enclosure geckos reached these temperatures within the first two months following release. No adjustment period was

detected in enclosure geckos' basking behaviour suggesting that visitors searching for and observing the geckos within the enclosure (although not tested for), may not be disturbing geckos to the point where their basking behaviour was affected. The enclosure size was found to be able to support at least eight jewelled geckos without resulting in a loss of condition over a 2-month period or inducing aggressive interactions. It is predicted however, that as the individuals within the enclosure age, they may naturally start to look for more space. Management recommendations include quantifying and monitoring the green skink population within the enclosure to ensure competition for food does not arise and planting an additional tall, well-developed *Coprosma* or mānuka shrub in the north side of the enclosure to encourage geckos to utilise the suitable thermal environment on that side. Of particular interest is to continue monitoring the body condition index and inter-specific behaviour of the translocated population to ensure the suitability of the enclosure long-term, especially as geckos age, start to reproduce and now that the density of geckos has increased to ten individuals.

CHAPTER 4

General Discussion

Summary of the Main Findings

Understanding the short and long-term implications of translocation methods used, and assessing the suitability of the release site, is essential when refining best translocation practices for a species. I examined the influence of the release method used on the stage of translocation success (based on the criteria of Miller *et al.*, 2014) at each release site for jewelled geckos within Orokonui Ecosanctuary, Dunedin, New Zealand. In addition, I assessed the suitability of Orokonui Ecosanctuary's new jewelled gecko enclosure in terms of enabling and promoting natural behaviour.

The release method used (penned versus hard release) did not influence the establishment of a population, the stage of translocation success reached or the long-term dispersal of founder individuals, 9 years following release. Evidence of annual reproduction however differed. The number of subadults was similar between sites (with one, two and three subadults sighted at the 2009 penned, 2012 hard release and 2012 penned release sites) however, a clear difference in neonates/juveniles sighted between the 2009/2012 penned (seven and eight individuals) and hard release sites (zero sighted). Both the 2012 hard release and penned (Sites 2 and 3) were close to Stage 3 (with 2-3 more sightings needed) whereas the 2009 penned release site (Site 1) required 14 more sightings. The enclosure's thermal environment was significantly cooler than those at Sites 1 and 2. However, all sites examined enabled the set point temperature range (the central 50% of temperatures jewelled geckos selected when under a thermal gradient; Christian *et al.*, 2016) to be reached, and natural basking behaviour was observed in the enclosure geckos. While the enclosure restricts individual home ranges, no aggressive interactions or decline in body condition were recorded in a manner that would indicate stocking density as an issue. Free-roaming geckos used a wider range of habitat types than available to the enclosure geckos and occupied significantly higher perch heights. Enclosure geckos were observed using only a proportion of the suitable basking habitat available with sightings clustered at two key points on the eastern and western sides of the enclosure and few observations made in the northern side and centre of the enclosure.

Implications of this Research for Jewelled Geckos and other *Naultinus* spp.

*Future Translocations of Green Geckos (*Naultinus *spp.)*

Penning for a minimum of four months in suitable, well-developed, native habitat is the recommended best practice for the translocation of green geckos (Knox *et al.*, 2017) to reduce post-release dispersal (Knox and Monks, 2014; Knox *et al.*, 2017). My research highlights the important role that propagule size has on the size of the population established, with 10 geckos sighted at the hard release site (11 released), but 40 geckos at the penned release site (42 released). Although the hard-released population has established at the release site and two founders were resighted, the number of sightings suggests that the established population is small. Small founder populations are at risk of genetic consequences, in particular being more susceptible to the effects of genetic drift and inbreeding, and the associated negative effects on species' fitness, extinction risk and evolutionary potential (Miller, 2009; Jamieson and Lacy, 2012).

My research also sparks the question: Is penning green geckos prior to release necessary? Although penning appears to have little effect on a population establishing at the release site long-term, it has a significant effect on reducing post-release dispersal short-term (Knox and Monks, 2014). The key benefit of reduced short-term dispersal is aiding initial monitoring following the release, which will likely assist in determining when stages 1 and 2 of Miller *et al.'s* (2014) criteria for translocation success (Stage 1: survival and growth of individuals and Stage 2: reproduction by non-gravid founders) are reached. In addition, of the eight green gecko translocations prior to 2011 that used a hard release method, only one founder individual was resighted (with low to high search effort; Knox and Monks, 2014), which suggests the establishment of the 2012 hard release population confirmed in my study, is highly unusual. The key difference between the established populations at the penned and hard release sites within Orokonui Ecosanctuary, is the observed population size (2009 penned = 17 individuals sighted (with a propagule size of 30 geckos), 2012 hard release = 10 (11 founders), 2012 penned = 40 (42 founders)). The close ratio between individuals sighted in my study and the number of founder individuals release (propagule size) highlights the need to translocate a large propagule size in addition to a penned release method, to promote population growth and reduce genetic complications that may arise from a small population size in the future.

Future Surveys for Green Geckos

Jewelled gecko detection was highest on sunny days in winter. Considering all New Zealand green gecko species are arboreal and diurnal basking species, it is likely that this can be extrapolated to all green gecko species (Bels and Russell, 2019). I suspect that during the warmer months, when the sun is directly above the vegetation for longer, geckos are using the tops of the vegetation more and are therefore less visible to observers. Due to the cryptic nature of New Zealand's green gecko species, surveys to resight individuals following translocation, especially in the longer-term when dispersal is likely, are time consuming. To maximise efficiency and lower any associated costs, I recommend conducting green gecko surveys on sunny days throughout winter and suggest that a combination of day surveys and night spotting are used. The search time required will vary depending on the search goal, release method used, propagule size, the release or pen area, habitat structure and complexity. My research also showed a threshold of search effort where 95% of the total number of geckos sighted (that were detectable) were found, before search effort per new gecko sighted increased greatly. This threshold was reached after 36 searches (and 159 person hours) out of 75 searches (and 201 person hours). The search effort required to reach this threshold will be dependent on factors such as time of year, observer experience, release method, release area, time since release and propagule size. However, this study may inform a baseline search effort required to sight 95% of the total number of detectable geckos after 75 searches, 9 years following release of 42 jewelled geckos that were penned in a 665m^2 pen for 9 months. This search effort could be adapted and used to guide the search effort for future monitoring programmes following green gecko translocations.

Design of future enclosures for green geckos

To address both animal welfare, conservation, monetary and/or advocacy goals associated with holding captive species, several factors need to be taken into consideration. To address these equally, all holders of captive species (private collectors, zoos, aquariums and ecosanctuaries) need to find a balance between providing entertainment, effective education, generating a profit and social and monetary support for conservation efforts, all in a way that promotes the animals' natural behaviour and reduces or eliminates daily sources of stress and anxiety. The design of such environments for captive species is not only of interest to conservation managers but also researchers working with captive animals in the lab and the public (Melfi *et al.,* 2004). Orokonui Ecosanctuary's green gecko enclosure is the first of its design: outdoor, open-top, with no supplementation (water or food) and providing suitable

jewelled gecko habitat, most of which had been growing in situ for 12 years prior to enclosure construction. The absence of any aggressive interactions and an increase in body condition index for all enclosure geckos following release (except for one that showed a negligible decrease) suggests that the enclosure (a 50m^2 vegetated area) is able to support eight sub-adult jewelled geckos without inducing abnormal or aggressive behaviour. This research highlights the great potential such an enclosure design holds for reaching the balance between advocacy, captive breeding and good animal welfare, which can be replicated for future jewelled gecko enclosures. However, the thermal environment within the enclosure was significantly cooler than two of the three release sites geckos occupied in the wider ecosanctuary. Outdoor enclosures created primarily for advocacy will likely be at sites where the surrounding environment is open and exposed for optimum viewing. This highlights the need to assess the suitability of an outdoor enclosure from a thermal perspective and to ensure the placement of the enclosure itself and the habitat inside provides sufficient basking opportunities for all individuals within to reach their set-point temperature.

Recommendations for Management of Jewelled Geckos at Orokonui Ecosanctuary

I recommend that periodic searches are conducted at the three release sites to confirm that Stage 3: population growth (of Miller *et al.*'s 2014 criteria for translocation success) has been reached at Sites 2 and 3 and to determine when Stage 4 is reached. Details around if and when these stages are reached by the Orokonui Ecosanctuary populations will provide further support for the release strategy and design used. This knowledge will also have implications for shaping future green gecko translocations to protected areas and the long-term monitoring program used (guiding the search effort required and recommended timing between surveys). I also recommend that a large, well developed specimen of *Coprosma* (either *C. dumosa* or another *C. propinqua*) or manuka shrub (at least 2m tall to provide a perch height commonly used by free-roaming geckos) is planted in the northern side of the enclosure where few observations have been made, to give the geckos more opportunities to utilise the thermal environment on this side. I also suggest that the long-term behaviour, interactions, growth rate and body condition index of enclosure geckos are monitored at least twice a year, especially as geckos age, reach reproductive maturity and now the enclosure population is fully stocked with 10 geckos. Confirmation of mating and reproduction once enclosure geckos are reproductively mature is also necessary, to confirm that the enclosure promotes natural reproductive behaviours.

Furthermore, Orokonui Ecosanctuary staff intend to translocate any enclosure-born geckos to the wider ecosanctuary to supplement the established populations of free-roaming individuals. I detected 80 jewelled geckos in the wider sanctuary, with populations established around all three release sites and 1-6 individuals at four new sites (>50m from the pen or hard release site boundaries). I suggest that this known distribution is used to direct where enclosure born geckos are released in the wider ecosanctuary. It may be beneficial to supplement Site 2, the release site with the smallest observed population. Supplementing new sites may also be of interest, although there may be genetic considerations as the observed populations at these sites are small and in two of the sites, comprised only a single individual.

Limitations of this Research

Sighting bias was a key limitation to this research. It was difficult to infer the true ratio of neonates, juveniles, subadults and adults present within Orokonui, as larger geckos are easier to detect, which is likely to explain the larger number of adult geckos observed in my study. The habitat structure, density and complexity in areas at all three sites also made detection difficult. The estimation of total number of geckos observed for Site 3 are restricted by the low detection rates in these difficult environments, and are therefore likely underestimates. Assessing translocation success at Site 1 is also likely hindered by a large area of tall manuka (~7m high) that surrounded the penned area.

The tracking segment of the study was severely limited by the season the research was conducted in and the low sighting rate for subadults. Initially Orokonui staff intended to translocate ten subadults and I intended to attach transmitters to five enclosure geckos and an additional ten free-roaming subadults (sourced from the three release sites) to compare the movements and basking behaviour of subadults between the enclosure and the wider ecosanctuary. Throughout the study, only 13 subadults were sighted therefore the above goal was unable to be achieved. Furthermore, as the enclosure was completed in December 2020, searching for subadults occurred over summer (when detection was the lowest), and many of the subadults that had been sighted in the cooler months in 2020, were unable to be resighted. For these reasons, five neonates and one subadult were translocated to the enclosure in December 2020 and then two additional subadults were located and translocated late January 2021. To make use of the transmitters and better understand free-roaming gecko movements, transmitters were attached to ten adults and one subadult (which was then translocated into the enclosure). Only one subadult translocated into the enclosure was large enough to have a

transmitter attached however, that individual had already been tracked for 3 weeks in the wider ecosanctuary, therefore could not be tracked again following release into the enclosure due to ethical considerations.

I also intended to calculate the body condition index (BCI) for free-roaming geckos in the same age brackets as the enclosure geckos when first sighted following the completion of the enclosure, and again at the end of the study, to compare with changes in BCI measured in enclosure geckos. Direct comparisons however were limited by the ability to resight the same free-roaming neonates/juveniles throughout the study (likely exacerbated by the study being conducted in summer, when detection rates were the lowest). Overall, only one free-roaming neonate was caught, weighed, measured and then recaptured at the end of the study to determine a change in body condition index. In addition, only one free-roaming neonate (of 14 individuals) was resighted at least 5 times for an MCP to be estimated. Therefore, the sample size of movements recorded and BCI measured for free-roaming neonates and subadults to directly compare with those measured in enclosure geckos, was limited to a change in BCI and an estimated MCP for one neonate and an MCP for one enclosure gecko prior to and following release into the enclosure (both in summer). The final limitation was a lack of replication when assessing the influence the release method (penned versus hard) used on the stage of translocation success reached. There was only one hard release translocation and two penned, however time of release was an additional factor to take into account. With the time of release and release method combined, there was no replication: one penned release 11 years ago, one penned release 9 years ago and one hard release 9 years ago.

Directions for Future Research

It is evident that research to determine what factors drive the establishment of a hard released green gecko population (such as habitat suitability at the release site, area founders are hard released into, life history stage and sex ratio of founder population and ease of gecko detectability at release site) is required to determine the true benefits of penning. To do so in an experimental study design will be difficult, as avoiding future translocation failures is of the highest priority and based on past experiences (summarised in Knox and Monks, 2014), additional hard releases may be risky. I therefore suggest a retrospective study is first conducted to try to identify the causes of failure for the previous green gecko translocations that used a hard release method. Also of interest, would be to determine how individual geckos find each other (e.g., pheromonal communication) and over what distance geckos are

able to find one another during the mating season. This knowledge will aid in determining the area green geckos should be released into, to promote reproduction and therefore the growth of the translocated population.

The low detection rates in summer and the low detectability of jewelled geckos in tall, dense and inaccessible habitat highlights the potential need for Miller *et al.'s* (2014) criteria for translocation success to accommodate cryptic species, like green geckos. With such species where detection is low, it is rare that the number of individuals sighted represents the number of individuals present within a population (Thompson, 2004). To take this disparity into account, it is suggested that a population abundance estimate that exceeds the propagule size, should also be considered as viable evidence that Stage 3 had been reached.
Developing more effective and efficient methods for the detection of jewelled geckos in tall, dense and inaccessible habitat (in particular forest canopies), would be valuable in improving monitoring programs following green gecko translocations, both short and long term. Habitat complexity following translocations often hinders observers' abilities to accurately determine the presence and/or size of the established population, as seen at Site 1 in this study. While the value of more effective and efficient detection methods for green geckos was highlighted a decade ago (in Knox, 2011), there appears to be no published advances in monitoring techniques (beyond spotlighting at night and visual day surveys) to reliably detect green geckos and estimate abundance in such difficult environments. While selecting habitat that enhances post-release visual monitoring can assist in assessing translocation success, this may reduce the habitat quality available to geckos and subsequently increase their vulnerability to predation. The development of such methods would aid in the detection and monitoring of all New Zealand's green geckos (being cryptic, diurnal and arboreal species).

Also of value, would be to determine the effect of transmitter attachment for 3 weeks using the adhesive backpack design (the standard attachment method for green geckos; Van Winkel and Ji, 2014) on skin sloughing in jewelled geckos. Signs of skin sloughing and scale loss following the removal of a transmitter have been reported in previous studies tracking jewelled geckos (Schneyer, 2001; Salmon 2002) but not others (Hare *et al.,* 2007; Knox and Monks *et al.,* 2014; Van Winkel and Ji, 2014; Knox *et al.,* 2017). My study reported the strongest evidence of skin sloughing due to transmitter attachment, with various degrees of skin sloughing beneath the transmitter or tape attachment seen in three geckos 16-20 days following attachment. Four of the five remaining geckos showed the first signs of the

sloughing process (discoloured skin beneath the transmitter, including the individual that had already undergone a full shed during tracking). Research aimed at understanding the consequences of triggering sloughing (on stress experienced and any influence that may have on natural behaviour and movements) in jewelled geckos would be valuable to better inform transmitter attachment designs for green geckos.

Conclusions

In this study the 2012 penned and hard release translocations of jewelled gecko to Orokonui Ecosanctuary were confirmed to have almost reached Stage 3 (population growth) of the criteria of Miller *et al.* (2014) for translocation success. Penning geckos prior to release did not have a detectable effect on the establishment of a population, the stage of translocation success reached or the long-term dispersal of founder individuals, 9 years following release. These findings highlight the fact that penning appears to have less of an effect than propagule size on the size of the established population long-term (although the propagule size between sites is a confounding factor). Ensuring that captive environments are designed to provide visitors with a close-up experience, educate the public on the conservation of the captive species, whilst also creating a naturalistic enclosure that enables and promotes natural behaviours, is integral. This however relies on careful planning and assessing the suitability of the enclosure following translocation within and learning from other captive enclosure designs. In New Zealand, indoor enclosures are most commonly used; however, my research implies that it is possible to create an outdoor, naturalistic, open-top and un-supplemented green gecko enclosure that promotes natural behaviour and offers advocacy opportunities, at least in the short-term (<two months following release).

References

Anderson, U. S., Benne, M., Bloomsmith, M. A., & Maple, T. L. (2002). Retreat space and human visitor density moderate undesirable behavior in petting zoo animals. *Journal of Applied Animal Welfare Science*, *5*(2), 125-137.

Angeli, N. F., Lundgren, I. F., Pollock, C. G., Hillis-Starr, Z. M., & Fitzgerald, L. A. (2018). Dispersal and population state of an endangered island lizard following a conservation translocation. *Ecological Applications*, *28*(2), 336-347.

Angilletta Jr, M. J., Steury, T. D., & Sears, M. W. (2004). Temperature, growth rate, and body size in ectotherms: fitting pieces of a life-history puzzle. *Integrative and comparative biology*, *44*(6), 498-509.

Baker, K. C. (1997). Straw and forage material ameliorate abnormal behaviors in adult chimpanzees. *Zoo Biology: Published in affiliation with the American Zoo and Aquarium Association*, *16*(3), 225-236.

Bakken, G. S., & Angilletta Jr, M. J. (2014). How to avoid errors when quantifying thermal environments. *Functional Ecology*, *28*(1), 96-107.

Bakken, G. S., & Gates, D. M. (1975). Heat-transfer analysis of animals: some implications for field ecology, physiology, and evolution. In *Perspectives of biophysical ecology* (pp. 255-290). Springer, Berlin, Heidelberg.

Ballantyne, R., & Packer, J. (2011). Using tourism free-choice learning experiences to promote environmentally sustainable behaviour: the role of post-visit 'action resources'. *Environmental Education Research*, *17*(2), 201-215.

Ballantyne, R., Packer, J., & Falk, J. (2011). Visitors' learning for environmental sustainability: Testing short-and long-term impacts of wildlife tourism experiences using structural equation modelling. *Tourism management*, *32*(6), 1243-1252.

Ballantyne, R., Packer, J., Hughes, K., & Dierking, L. (2007). Conservation learning in wildlife tourism settings: Lessons from research in zoos and aquariums. *Environmental Education Research*, *13*(3), 367-383.

Bashaw, M. J., Gibson, M. D., Schowe, D. M., & Kucher, A. S. (2016). Does enrichment improve reptile welfare? Leopard geckos (*Eublepharis macularius*) respond to five types of environmental enrichment. *Applied animal behaviour science*, *184*, 150-160.

Bell, T. P., & Herbert, S. M. (2017). Establishment of a self-sustaining population of a long-lived, slow-breeding gecko species (Diplodactylidae: *Hoplodactylus duvaucelii*) evident 15 years after translocation. *Journal of Herpetology*, *51*(1), 37-46.

Bellis, J., Bourke, D., Maschinski, J., Heineman, K., & Dalrymple, S. (2020). Climate suitability as a predictor of conservation translocation failure. *Conservation Biology*, *34*(6), 1473-1481.

Bels, V., & Russell, A. (Eds.). (2019). *Behavior of Lizards: Evolutionary and Mechanistic Perspectives*. CRC Press.

Benesch, A. R., Munro, U., Krop, T., & Fleissner, G. (2010). Seasonal changes in the behaviour and circadian rhythms in activity and behaviour of captive koalas Phascolarctos cinereus. *Biological Rhythm Research*, *41*(4), 289-304.

Benn, A. L., McLelland, D. J., & Whittaker, A. L. (2019). A review of welfare assessment methods in reptiles, and preliminary application of the welfare quality® protocol to the pygmy blue-tongue skink, *Tiliqua adelaidensis*, using animal-based measures. *Animals*, *9*(1), 27.

Berger-Tal, O., Blumstein, D. T., & Swaisgood, R. R. (2020). Conservation translocations: a review of common difficulties and promising directions. *Animal Conservation*, *23*(2), 121-131.

Besson, A. A., & Cree, A. (2011). Integrating physiology into conservation: an approach to help guide translocations of a rare reptile in a warming environment. *Animal Conservation*, *14*(1), 28-37.

Bonnet, X., & Naulleau, G. (1994). A body condition index (BCI) in snakes to study reproduction. *C. R. Acad. Sci III-Vie*, *317*(1), 34-41.

Bull, C. M., & Baghurst, B. C. (1998). Home range overlap of mothers and their offspring in the sleepy lizard, *Tiliqua rugosa*. *Behavioral Ecology and Sociobiology*, *42*(5), 357-362.

Burgess, T. L., Gartrell, B. D., & Blanchard, B. (2009). A survey of the husbandry of captive tuatara (Sphenodon spp.) in relation to factors implicated in nutritional secondary hyperparathyroidism. *New Zealand veterinary journal*, *57*(6), 378-382.

Burghardt, G. M. (2013). Environmental enrichment and cognitive complexity in reptiles and amphibians: concepts, review, and implications for captive populations. *Applied Animal Behaviour Science*, *147*(3-4), 286-298.

Calenge, C. (2006). The package adehabitat for the R software: a tool for the analysis of space and habitat use by animals. Ecological Modelling 197:516–519.

Cassinello, J., & Pieters, I. (2000). Multi-male captive groups of endangered dama gazelle: Social rank, aggression, and enclosure effects. *Zoo Biology: Published in affiliation with the American Zoo and Aquarium Association*, *19*(2), 121-129.

Chamove, A. S., Anderson, J. R., Morgan-Jones, S. C., & Jones, S. P. (1982). Deep woodchip litter: Hygiene, feeding, and behavioral enhancement in eight primate species.

Chapple, D. G. (Ed.). (2016). *New Zealand Lizards*. Springer International Publishing.

Chiszar, D., Smith, H. M., & Radcliffe, C. W. (1993). Zoo and laboratory experiments on the behavior of snakes: assessments of competence in captive-raised animals. *American Zoologist*, *33*(2), 109-116.

Christian, K. A., Tracy, C. R., & Tracy, C. R. (2016). Body temperatures and the thermal environment. *Reptile ecology and conservation: a handbook of techniques. Oxford University Press, Oxford, UK*, 337-351.

Chukwuka, C. O., Virens, J., & Cree, A. (2019). Accuracy of an inexpensive, compact infrared thermometer for measuring skin surface temperature of small lizards. *Journal of thermal biology*, *84*, 285-291.

Clubb, R., & Mason, G. (2002). *A review of the welfare of zoo elephants in Europe*. Horsham, West Sussex: RSPCA.

Clubb, R., & Mason, G. J. (2007). Natural behavioural biology as a risk factor in carnivore welfare: How analysing species differences could help zoos improve enclosures. *Applied Animal Behaviour Science*, *102*(3-4), 303-328.

Cong, L., Wu, B., Morrison, A. M., Shu, H., & Wang, M. (2014). Analysis of wildlife tourism experiences with endangered species: An exploratory study of encounters with giant pandas in Chengdu, China. *Tourism management*, *40*, 300-310.

Cree, A. (1994). Low annual reproductive output in female reptiles from New Zealand. *New Zealand journal of zoology*, *21*(4), 351-372.

Cree A. (2003) *Reptiles of southern forests and shrublands*. *In*: Darby J., Fordyce R.E., Mark A.F., Probert K. & Townsend C. *The natural history of southern New Zealand*. Dunedin, N.Z. University of Otago press.

Cree, A., & Hare, K. M. (2016a). Reproduction and life history of New Zealand lizards. In *New Zealand Lizards* (pp. 169-206). Springer, Cham.

Cree, A., & Hare, K. M. (2016b). Maternal basking regime has complex implications for birthdate and offspring phenotype in a nocturnally foraging, viviparous gecko. *Journal of Experimental Biology*, *219*(18), 2934-2943.

DeGregorio, B., Moody, R., & Myers, H. (2020). Soft Release Translocation of Texas Horned Lizards (*Phrynosoma cornutum*) on an Urban Military Installation in Oklahoma, United States. *Animals*, *10*(8), 1358.

Dent, E. (2016). The impacts of an introduced mammalian predator (*Mus musculus*) on tree

weta (*Hemideina trewicki*) and skinks (*Oligosoma polychroma, Oligosoma infrapunctatum and Oligosoma lineoocellatum*) in Cape Sanctuary, Hawkes Bay.

Dirzo, R., Young, H. S., Galetti, M., Ceballos, G., Isaac, N. J., & Collen, B. (2014). Defaunation in the Anthropocene. *science*, *345*(6195), 401-406.

Dzialowski, E. M. (2005). Use of operative temperature and standard operative temperature models in thermal biology. *Journal of Thermal Biology*, *30*(4), 317-334.

Dodd Jr, C. K., & Dorazio, R. M. (2004). Using counts to simultaneously estimate abundance and detection probabilities in a salamander community. *Herpetologica*, *60*(4), 468-478.

Dodd Jr, C. K., & Seigel, R. A. (1991). Relocation, repatriation, and translocation of amphibians and reptiles: are they conservation strategies that work? *Herpetologica*, 336-350.

Doneley, B., Monks, D., Johnson, R., Carmel, B., & Wiley, J. (Eds.). (2018). *Reptile medicine and surgery in clinical practice*. Wiley Blackwell.

Duggan, L. (1991). *Emergence Behaviour of Naultinus Gemmeus, the Jewelled Gecko, on Otago Peninsula: A Research Report Submitted in Partial Fulfilment of the Requirements for the Diploma in Wildlife Management* (Doctoral dissertation, University of Otago, Department of Zoology).

Ebrahimi, M., & Bull, C. M. (2012). Food supplementation reduces post-release dispersal during simulated translocation of the endangered pygmy bluetongue lizard *Tiliqua adelaidensis*. *Endangered Species Research*, *18*(2), 169-178.

Eifler, D. A., & Eifler, M. A. (1999). The influence of prey distribution on the foraging strategy of the lizard *Oligosoma grande* (Reptilia: Scincidae). *Behavioral Ecology and Sociobiology*, *45*(6), 397-402.

Ellinger, N., Schlatte, G., Jerome, N., & Hödl, W. (2001). Habitat use and activity patterns of the neotropical arboreal lizard *Tropidurus* (= *Uracentron*) *azureus werneri* (Tropiduridae). *Journal of Herpetology*, 395-402.

Fitzgerald, L. A., Treglia, M. L., Angeli, N., Hibbitts, T. J., Leavitt, D. J., Subalusky, A. L., ... & Hillis-Starr, Z. (2015). Determinants of successful establishment and post-translocation dispersal of a new population of the critically endangered St. Croix ground lizard (*Ameiva polops*). *Restoration Ecology*, *23*(6), 776-786.

Fleming, G. J., Isaza, R., Spire, M. F., & Heard, D. J. (2003). The use of digital thermography for environmental evaluation of reptile enclosures. *Journal of Herpetological Medicine and Surgery*, *13*(1), 38-42.

Flynn-Plummer, T. P., & Monks, J. M. (2021). Penned release reduces area use by translocated barking geckos (Naultinus punctatus). *New Zealand Journal of Ecology*, *45*(1).

Gartrell, B. D., Ahn, J. Y., Khude, R., Dougherty, N., Johnson, K., McCutchan, J., ... & Hunter, S. (2020). Thermal burns of the spectacle associated with supplementary heating in native New Zealand geckos. *New Zealand veterinary journal*, *68*(2), 126-133.

Germano, J., Barlow, S., Castro, I., Colbourne, R., Cox, M., Gillies, C., ... & Yong, S. (2018). Kiwi Recovery Plan 2018–2028 Mahere Whakaora Kiwi 2018–2028. *Wellington: New Zealand Department of Conservation*.

Germano, J. M., & Bishop, P. J. (2009). Suitability of amphibians and reptiles for translocation. *Conservation biology*, *23*(1), 7-15.

Gibbs, G. W. (2009). The end of an 80-million year experiment: a review of evidence describing the impact of introduced rodents on New Zealand's 'mammal-free' invertebrate fauna. *Biological Invasions*, *11*(7), 1587-1593.

Gibson, S., Penniket, S., & Cree, A. (2015). Are viviparous lizards from cool climates ever exclusively nocturnal? Evidence for extensive basking in a New Zealand gecko. *Biological Journal of the Linnean Society*, *115*(4), 882-895.

Gilbert, T., & Soorae, P. S. (2017). The role of zoos and aquariums in reintroductions and other conservation translocations.

Grant, T. D., & Hudson, R. D. (2015). West Indian iguana *Cyclura* spp. reintroduction and recovery programmes: zoo support and involvement. *International zoo yearbook*, *49*(1), 49-55.

Gusset, M., & Dick, G. (2011). The global reach of zoos and aquariums in visitor numbers and conservation expenditures. *Zoo Biology*, *30*(5), 566-569.

Hare, K. M., Borrelle, S. B., Buckley, H. L., Collier, K. J., Constantine, R., Perrott, J. K., ... & Towns, D. R. (2019). Intractable: species in New Zealand that continue to decline despite conservation efforts. *Journal of the Royal Society of New Zealand*, *49*(3), 301-319.

Hare, K. M., & Cree, A. (2016). Thermal and metabolic physiology of New Zealand lizards. In *New Zealand Lizards* (pp. 239-267). Springer, Cham.

Hare, K. M., Hoare, J. M., & Hitchmough, R. A. (2007). Investigating natural population dynamics of Naultinus manukanus to inform conservation management of New Zealand's cryptic diurnal geckos. *Journal of Herpetology*, *41*(1), 81-93.

Hawkins, M., & Willlemsen, M. (2004). Environmental enrichment for amphibians and reptiles. In *ASZK Reptile Enrichment Workshop 2004*.

Herrelko, E. S., Buchanan-Smith, H. M., & Vick, S. J. (2015). Perception of available space during chimpanzee introductions: Number of accessible areas is more important than enclosure size. *Zoo biology*, *34*(5), 397-405.

Hitchmough, R., Barr, B. P., Knox, C., Lettink, M., Monks, J. M., Patterson, G. B., Reardon, J. T., van Winkel. D., Rolfe, J., & Pascale, M. (2021). *Conservation status of New Zealand reptiles, 2021*. Publishing Team, Department of Conversation.

Hoare, J. M., Pledger, S., Keall, S. N., Nelson, N. J., Mitchell, N. J., & Daugherty, C. H. (2006). Conservation implications of a long-term decline in body condition of the Brothers Island tuatara (Sphenodon guntheri). *Animal Conservation*, *9*(4), 456-462.

Horton, G. M. J., Malinowski, K., Burgher, C. C., & Palatini, D. D. (1991). The effect of space allowance and sex on blood catecholamines and cortisol, feed consumption and average daily gain in growing lambs. *Applied animal behaviour science*, *32*(2-3), 197-204.

Innes, J., Fitzgerald, N., Binny, R., Byrom, A., Pech, R., Watts, C., ... & Burns, B. (2019). New Zealand ecosanctuaries: types, attributes and outcomes. *Journal of the Royal Society of New Zealand*, *49*(3), 370-393.

IUCN/SSC. (2013). Guidelines for Reintroductions and Other Conservation Translocations. *Gland, Switzerland: IUCN Species Survival Commission*.

Jamieson, I. G., & Lacy, R. C. (2012). Managing genetic issues in reintroduction biology. *Reintroduction biology: integrating science and management*, *12*, 441.

Jarvie, S., Besson, A. A., Seddon, P. J., & Cree, A. (2014). Assessing thermal suitability of translocation release sites for egg-laying reptiles with temperature-dependent sex determination: a case study with tuatara. *Animal Conservation*, *17*, 48-55.

Jewell, T. (2011). A photographic guide to reptiles and amphibians of New Zealand. Revised edn. Photographs by Rod Morris. New Holland Publishers, Auckland

Jewell, T., & McQueen, S. (2007). *Habitat characteristics of jewelled gecko (Naultinus gemmeus) sites in dry parts of Otago*. Science and Technical Pub., Department of Conservation.

King, C. M. (1984). *Immigrant killers: introduced predators and the conservation of birds in New Zealand*. Oxford University Press, USA.

Kleiman, D. G., Thompson, K. V., & Baer, C. K. (Eds.). (2010). *Wild mammals in captivity: principles and techniques for zoo management*. University of Chicago Press.

Knox, C. D. (2011). *Habitat requirements of the jewelled gecko (Naultinus gemmeus): effects of grazing, predation and habitat fragmentation* (MSc thesis, University of Otago).

Knox, C. D. (2014). Jewelled geckos (*Naultinus gemmeus*) in the tussockland of Otago. In BioGecko, issue 2.

Knox, C. D. (2019). Monitoring and survey for jewelled geckos and tautuku geckos in Otago 2018-2019. *Wildland Consultants Ltd Contract Report No. 4440b*. Prepared for the Department of Conservation.

Knox, C. D., Cree, A., & Seddon, P. J. (2012). Direct and indirect effects of grazing by introduced mammals on a native, arboreal gecko (Naultinus gemmeus). *Journal of Herpetology*, *46*(2), 145-152.

Knox, C. D., Cree, A., & Seddon, P. J. (2013). Accurate identification of individual geckos (Naultinus gemmeus) through dorsal pattern differentiation. *New Zealand Journal of Ecology*, 60-66.

Knox, C. D., Jarvie, S., Easton, L. J., & Monks, J. M. (2017). Soft-Release, but Not Cool Winter Temperatures, Reduces Post-Translocation Dispersal of Jewelled Geckos. *Journal of Herpetology*, *51*(4), 490-496.

Knox, C. D., & Monks, J. M. (2014). Penning prior to release decreases post-translocation dispersal of jewelled geckos. *Animal Conservation*, *17*, 18-26.

Knox, C. D., & Rate, S. (2018). Monitoring and survey for jewelled geckos in Otago 2017-2018. *Wildland Consultants Ltd Contract Report No. 4440*. Prepared for the Department of Conservation.

Knox, C. D., Smith, E., & Lloyd, K. (2019). Captive management plan for a breeding enclosure and public display of jewelled geckos at Ōrokonui Ecosanctuary, Dunedin. *Wildland Consultants Ltd Contract Report No. 5147a*. Prepared for Ōrokonui Ecosanctuary.

Koolhaas, J. M., Bartolomucci, A., Buwalda, B., de Boer, S. F., Flügge, G., Korte, S. M., ... & Richter-Levin, G. (2011). Stress revisited: a critical evaluation of the stress concept. *Neuroscience & Biobehavioral Reviews*, *35*(5), 1291-1301.

Krebs, C.J. (2014). Chapter 2 Estimating Abundance and Density: Mark-Recapture Techniques. In C. J. Krebs (Ed.). *Ecological Methodology* (3rd ed. pp. 24-78).

Kuppert, S. (2013). Providing enrichment in captive amphibians and reptiles: Is it important to know their communication?

Lardner, B., Rodda, G. H., Adams, A. A. Y., Savidge, J. A., & Reed, R. N. (2015). Detection rates of geckos in visual surveys: turning confounding variables into useful knowledge. *Journal of Herpetology*, *49*(4), 522-532.

Lettink, M., O'Donnell, C. F., & Hoare, J. M. (2011). Accuracy and precision of skink counts from artificial retreats. *New Zealand Journal of Ecology*, 236-246.

Liordos, V., Kontsiotis, V. J., Anastasiadou, M., & Karavasias, E. (2017). Effects of attitudes and demography on public support for endangered species conservation. *Science of the Total Environment*, *595*, 25-34.

Lucas, C., & Stanyon, B. (2017). Improving the welfare of African elephants *Loxodonta africana* in zoological institutions through enclosure design and husbandry management: an example from Blair Drummond Safari and Adventure Park. *International Zoo Yearbook*, *51*(1), 248-257.

Mallapur, A., & Chellam, R. (2002). Environmental influences on stereotypy and the activity budget of Indian leopards (Panthera pardus) in four zoos in southern India. *Zoo Biology: Published in affiliation with the American Zoo and Aquarium Association*, *21*(6), 585-595.

Marais, J. & Morgan, D.R. (1990). Reptile Husbandry. In: Husbandry '88. Proceedings of the First H.A.A. Reptile Husbandry Symposium. *Journal of the Herpetological Association of Africa 38*.

Marion, K. R. (1982). Reproductive cues for gonadal development in temperate reptiles: temperature and photoperiod effects on the testicular cycle of the lizard *Sceloporus undulatus*. *Herpetologica*, 26-39.

Mason, G. J. (1991). Stereotypies: a critical review. *Animal behaviour*, *41*(6), 1015-1037.

Maxwell, S. L., Fuller, R. A., Brooks, T. M., & Watson, J. E. (2016). Biodiversity: The ravages of guns, nets and bulldozers. *Nature News*, *536*(7615), 143.

McClure, C. (2011). Testing translocation, detection and live trapping methods for New Zealand lizards. *Unpublished BSc honours thesis. Lincoln University, Lincoln*.

Melfi, V. A., McCormick, W., & Gibbs, A. (2004). A preliminary assessment of how zoo visitors evaluate animal welfare according to enclosure style and the expression of behavior. *Anthrozoös*, *17*(2), 98-108.

Miller, K. A. (2009). Founding events and the maintenance of genetic diversity in reintroduced populations.

Miller, K. A., Bell, T. P., & Germano, J. M. (2014). Understanding publication bias in reintroduction biology by assessing translocations of New Zealand's

herpetofauna. *Conservation Biology*, *28*(4), 1045-1056.

Monks, J., Knox, C., & Sidaway, K. (2017). Best practice techniques for the translocation of green geckos (*Naultinus* spp.).

Morgan, K. N., & Tromborg, C. T. (2007). Sources of stress in captivity. *Applied animal behaviour science*, *102*(3-4), 262-302.

Nelson, N. J., Briskie, J. V., Constantine, R., Monks, J., Wallis, G. P., Watts, C., & Wotton, D. M. (2019). The winners: species that have benefited from 30 years of conservation action. *Journal of the Royal Society of New Zealand*, *49*(3), 281-300.

Nelson, N. J., Hitchmough, R. A., & Monks, J. M. (2014). New Zealand reptiles and their conservation. *Austral Ark: the state of wildlife in Australia and New Zealand. Cambridge University Press, Cambridge*, 382-404.

O'Neill, P. (1989). A room with a view for captive primates: Issues, goals, related research and strategies.

Orokonui Ecosanctuary. (2020). The Orokonui Story. See https://orokonui.nz/About/The-Orokonui-Story. Accessed March 12th 2021.

Padgham, M., & Sumner, M. D. (2020). Geodist: fast, dependency-free geodesic distance calculations. R package version 0.0.4.

Penniket, S., & Cree, A. (2015). Adherence to Bergmann's rule by lizards may depend on thermoregulatory mode: support from a nocturnal gecko. *Oecologia*, *178*(2), 427-440.

Pérez-Buitrago, N., & Sabat, A. (2007). Natal dispersal, home range and habitat use of hatchlings of the Mona Island iguana (*Cyclura cornuta stejnegeri*). *Applied Herpetology*, *4*(4), 365.

Quadros, S., Goulart, V. D., Passos, L., Vecci, M. A., & Young, R. J. (2014). Zoo visitor effect on mammal behaviour: Does noise matter? *Applied Animal Behaviour Science*, *156*, 78-84.

Reardon, J. T., Whitmore, N., Holmes, K. M., Judd, L. M., Hutcheon, A. D., Norbury, G., & Mackenzie, D. I. (2012). Predator control allows critically endangered lizards to recover on mainland New Zealand. *New Zealand Journal of Ecology*, 141-150.

Rees, P. A. (2004). Low environmental temperature causes an increase in stereotypic behaviour in captive Asian elephants (*Elephas maximus*). *Journal of thermal biology*, *29*(1), 37-43.

Reinert, H. K. (1991). Translocation as a conservation strategy for amphibians and reptiles: some comments, concerns, and observations. *Herpetologica*, *47*(3), 357-363.

Richardson, K., Castro, I. C., Brunton, D. H., & Armstrong, D. P. (2015). Not so soft? Delayed release reduces long-term survival in a passerine reintroduction. *Oryx*, *49*(3), 535-541.

Rose, B. (1982). Lizard home ranges: methodology and functions. *Journal of Herpetology*, 253-269.

Salmon, M.N. (2002). Telemetric studies of the geckos *Hoplodactylus maculatus* and *Naultinus gemmeus*. Unpublished MSc thesis, University of Otago, Dunedin.

Schneyer, N. (2002). *Effects of avian predation and habitat degradation on the population dynamics of the jewelled gecko (Naultinus gemmeus) from the Every Scientific Reserve, Otago Peninsula, New Zealand* (MSc thesis, University of Otago).

Seddon, P. J., Soorae, P. S., & Launay, F. (2005). Taxonomic bias in reintroduction projects. *Animal Conservation*, *8*(1), 51-58.

Sherley, G. H., Stringer, I. A., & Parrish, G. R. (2010). *Summary of native bat, reptile, amphibian and terrestrial invertebrate translocations in New Zealand* (No. 303). Department of Conservation.

Sherwen, S. L., Magrath, M. J., Butler, K. L., & Hemsworth, P. H. (2015). Little penguins, *Eudyptula minor*, show increased avoidance, aggression and vigilance in response to zoo visitors. *Applied Animal Behaviour Science*, *168*, 71-76.

Shine, R., & Kearney, M. (2001). Field studies of reptile thermoregulation: how well do physical models predict operative temperatures? *Functional Ecology*, 282-288.

Spencer, N. J., Thomas, B. W., Mason, R. F., & Dugdale, J. S. (1998). Diet and life history variation in the sympatric lizards *Oligosoma nigriplantare polychroma* and *Oligosoma lineoocellatum*. *New Zealand journal of zoology*, *25*(4), 457-463.

Stamps, J. A., & Krishnan, V. V. (1998). Territory acquisition in lizards. IV. Obtaining high status and exclusive home ranges. *Animal Behaviour*, *55*(2), 461-472.

Summers, C. H. (2002). Social interaction over time, implications for stress responsiveness. *Integrative and Comparative Biology*, *42*(3), 591-599.

Sunday, J. M., Bates, A. E., Kearney, M. R., Colwell, R. K., Dulvy, N. K., Longino, J. T., & Huey, R. B. (2014). Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. *Proceedings of the National Academy of Sciences*, *111*(15), 5610-5615.

Swaisgood, R. R., & Schulte, B. A. (2010). Applying knowledge of mammalian social organization, mating systems, and communication to management. *Wild mammals in captivity: Principles and techniques for zoo management*, 329-343.

Sweetapple, P. J., & Nugent, G. (2007). Ship rat demography and diet following possum control in a mixed podocarp—hardwood forest. *New Zealand Journal of Ecology*, 186-201.

Tattersall, G. J. (2016). Infrared thermography: A non-invasive window into thermal physiology. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology*, *202*, 78-98.

Tetzlaff, S. J., Sperry, J. H., & DeGregorio, B. A. (2019). Effects of antipredator training, environmental enrichment, and soft release on wildlife translocations: a review and meta-analysis. *Biological conservation*, *236*, 324-331.

Thompson, W. L. (2004). Estimating abundance of rare or elusive species. *Sampling rare or elusive species: concepts, designs, and techniques for estimating population parameters*, *389*.

Tingley, R., Hitchmough, R. A., & Chapple, D. G. (2013). Life-history traits and extrinsic threats determine extinction risk in New Zealand lizards. *Biological Conservation*, *165*, 62-68.

Tokarz, R. R., & Summers, C. H. (2011). Stress and reproduction in reptiles. In *Hormones and reproduction of vertebrates* (pp. 169-213). Academic Press.

Towns, D. R., & Daugherty, C. H. (1994). Patterns of range contractions and extinctions in the New Zealand herpetofauna following human colonisation. *New Zealand journal of zoology*, *21*(4), 325-339.

Towns, D. R., Miller, K. A., Nelson, N. J., & Chapple, D. G. (2016). Can translocations to islands reduce extinction risk for reptiles? Case studies from New Zealand. *Biological Conservation*, *204*, 120-127.

Treglia, M. L. (2010). *A translocated population of the St. Croix ground lizard: analyzing its detection probability and investigating its impacts on the local prey base* (Doctoral dissertation, Texas A & M University).

Van der Meer, E., Van Loo, P. L. P., & Baumans, V. (2004). Short-term effects of a disturbed light–dark cycle and environmental enrichment on aggression and stress-related parameters in male mice. *Laboratory Animals*, *38*(4), 376-383.

Van Winkel, D. (2008). Efficiency of techniques for post-translocation monitoring of the Duvaucel's gecko (*Hoplodactylus duvaucelii*) and evidence of native avian predation on lizards: a thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Conservation Biology, Massey University, Auckland, New Zealand (Doctoral dissertation, Massey University).

Van Winkel, D., Baling, M., & Hitchmough, R. (2018). *Reptiles and amphibians of New Zealand: a field guide*. Auckland University Press.

Van Winkel, D., & Ji, W. (2014). Attaching radio-transmitters to Geckos: trials and tribulations. *Herpetological Review*, *45*(1), 13-17.

Vitt, L. J., van Loben Sels, R. C., & Ohmart, R. D. (1981). Ecological relationships among arboreal desert lizards. *Ecology*, *62*(2), 398-410.

Ward, S. J., Sherwen, S., & Clark, F. E. (2018). Advances in applied zoo animal welfare science. *Journal of Applied Animal Welfare Science*, *21*(sup1), 23-33.

Warwick, C. (1990). Reptilian ethology in captivity: observations of some problems and an evaluation of their aetiology. *Applied Animal Behaviour Science*, *26*(1-2), 1-13.

Warwick, C., Arena, P., Lindley, S., Jessop, M., & Steedman, C. (2013). Assessing reptile welfare using behavioural criteria. *In Practice*, *35*(3), 123-131.

Watts, C. H., Armstrong, D. P., Innes, J., & Thornburrow, D. (2011). Dramatic increases in weta (*Orthoptera*) following mammal eradication on Maungatautari–evidence from pitfalls and tracking tunnels. *New Zealand Journal of Ecology*, 261-272.

Weeks, A. R., Sgro, C. M., Young, A. G., Frankham, R., Mitchell, N. J., Miller, K. A., ... & Hoffmann, A. A. (2011). Assessing the benefits and risks of translocations in changing environments: a genetic perspective. *Evolutionary Applications*, *4*(6), 709-725.

Weir, L. A., Royle, J. A., Nanjappa, P., & Jung, R. E. (2005). Modelling anuran detection and site occupancy on North American Amphibian Monitoring Program (NAAMP) routes in Maryland. *Journal of Herpetology*, *39*(4), 627-639.

Whitaker T., Tocher M. & Blair T. (2002) Conservation of lizards in Otago Conservancy 2002–2007. Unpublished report, Department of Conservation. Wellington, 92p.

Wieser, W. (1973). *Effects of temperature on ectothermic organisms*. Springer Berlin Heidelberg.

Wilson, J. L., & Cree, A. (2003). Extended gestation with late-autumn births in a cool-climate viviparous gecko from southern New Zealand (Reptilia: *Naultinus gemmeus*). *Austral Ecology*, *28*(3), 339-348.

Wilson, D. J., & Lee, W. G. (2010). Primary and secondary resource pulses in an alpine ecosystem: snow tussock grass (*Chionochloa* spp.) flowering and house mouse (*Mus musculus*) populations in New Zealand. *Wildlife Research*, *37*(2), 89-103.

Wingfield, J. C. (2006). Control of behavioural strategies for capricious environments. *Essays in animal behaviour celebrating 50 years of Animal Behaviour*, 115-133.

Wingfield, J. C. (2013). Ecological processes and the ecology of stress: the impacts of abiotic environmental factors. *Functional Ecology*, *27*(1), 37-44.

Wright, R. K., & Cooper, E. L. (1981). Temperature effects on ectotherm immune responses. *Developmental & Comparative Immunology*, *5*, 117-122.

Yamaura, Y., Kery, M., & Royle, J. A. (2016). Study of biological communities subject to imperfect detection: bias and precision of community N-mixture abundance models in small-sample situations. *Ecological Research*, *31*(3), 289-305.

Appendices

Appendix 1: Enclosure Designs Used for Captive Green Geckos Throughout New Zealand

Introduction

Part of this thesis focused on confirming the suitability of Orokonui Ecosanctuary's enclosure design (chapter 3), which could be used to better inform future green gecko enclosure designs. An understanding of the current designs that are in use today is required to be able to apply these findings in the most effective way. The survey conducted as part of this thesis intended to collate information on how green geckos are most commonly displayed today and to use this information to: (1) Enable the identification of any common problems in the keeping of captive green geckos and information on how these issues have been resolved. (2) Compare Orokonui Ecosanctuary's enclosure design with those used for other captive green geckos (3) Apply designs and lessons learnt from previous designs to Orokonui's enclosure. (4) Apply any positive and negative effects of Orokonui's enclosure design on the jewelled geckos within to better inform green gecko enclosure designs in use today.

Methods

In November 2020, I received Human Ethics approval by the University of Otago to distribute an optional survey that aimed to collect data on the current designs used for green geckos (Naultinus spp.) in captivity in New Zealand. Of particular interest were the size of the enclosure, the vegetation and structures inside, the species of green gecko within and the number, sex and ages of the geckos. Information was also collected on how successful breeding had been, as well as the frequency of aggressive interactions and stress responses in the captive geckos and how these issues were mitigated through changes in enclosure design. The participants included private collectors of green geckos and professional keepers from zoos, ecosanctuaries and other institutions throughout New Zealand. In total, 13 professional keepers and members of the New Zealand Herpetological Society that were keepers of green geckos were requested to complete the survey via email. In addition, the survey and the request for participants was posted on the New Zealand Native Reptile Keepers' Facebook page. The survey was optional to all that were contacted, and was presented as a Word document with an information sheet approved

by the University of Otago Human Ethics Committee. The information sheet informed participants of the survey purpose, the targeted participants, what was expected of participants and what the information would be used for. There were two recruitment periods: in December 2020 (first contact) and June 2021 (when a follow-up email was sent to all professional keepers who did not respond to the first email, and another post was sent on the New Zealand Native Reptile Keepers' Facebook page).

Results and Discussion

In total, nine responses were collected (with information on 19 green gecko enclosures): six from professional (n = 5) and 13 from private collectors (n = 4, three private collectors had >1 green gecko enclosure). These responses revealed that there are captive green geckos in Kerikeri, Auckland, Waihi, Hamilton, Hawkes Bay, Wellington and Dunedin. Of the responses, *Naultinus grayii* and *N.* elegans (eight and five enclosures) were the most commonly held species (compared to three *N. gemmeus*, two *N. punctatus* and one *N. Stellatus* enclosure). Green gecko species were not mixed, however three enclosures reported cohabitation with between two and six other gecko or skinks (*Woodworthia maculata* (raukawa gecko), *Mokopirirakau granulatus* (forest gecko) or *Oligosoma moco* (Moko skink). Outdoor enclosures (n=15) were more common than indoor tanks or terrariums (n=4). On average, captive populations were comprised of four geckos (but ranged from one to eight geckos within a single enclosure). Adults dominated the reported captive populations (with only two enclosures holding subadults or neonates) and sex ratios were equal (1:1) or biased towards more females than males (Table A.1.1).

As all enclosures were closed (as opposed to open-top), the three-dimensional area (m^3) available to each gecko was calculated. Mean enclosure size (± SE) was 0.25 m^3 ± 0.07 m^3 and mean sizes were similar between enclosure types (indoor: 0.27 m^3; outdoor: 0.25 m^3). There is a difference however between the total enclosure size and the vegetated area available to geckos for use. The above areas may therefore be an overestimate of the space available to each gecko. A more comparable metric (between closed and open top enclosures) may be the two-dimensional space (mean of 0.21 m^2; indoor: 0.27 m^2, outdoor: 0.20 m^2). Professional and private enclosures held an average of three and four geckos. In contrast to the last of difference in enclosure size between enclosure type (reported above), private collectors' enclosures appear to be smaller (mean size of 0.46 m^3) than professional keepers' enclosures (1.24 m^3). In addition, collectors tended to have multiple green gecko enclosures (one, two, three and seven enclosures) whereas professional keepers often have one enclosure (Table A.1.1). These differences could be attributed to differences in motivations behind holding captive

green geckos. It is expected that advocacy and public viewing are the primary motivations for professionals whereas personal viewing and interest are likely to be the key motivations behind private collectors holding green geckos. Rehabilitation of mistreated green geckos was a reported motivation for at least one keeper from both groups.

Green geckos are also confined to an area during penned translocations, where a founder population is held within a penned area for a period of time (four months is considered the best practice for green geckos; Monks *et al.*, 2017). Published penned translocations have ranged in the space provided per gecko (from 5.3 m^2; Flynn-Plummer and Monks, 2021, to 30.8 m^2; Scott, 2016). Captive breeding and viewing enclosures (reported above) appear to be significantly smaller in size (total area and area per gecko) than temporary pens (Table A.1.1). No signs of behavioural or physical stress were reported; however, one collector has observed aggressive, territorial behaviour in *N. grayii* (males and some females), *N. stellatus*, *N. gemmeus* and *N. elegans* (private collector 1; Table A.1.1). Such behaviour has resulted in bite marks, bruising and the loss if tail tips. Introducing new males into the colonies was thought to be more problematic than females (who were reported to be easily accepted). Aggressive interactions were resolved by re-homing the individual(s) exhibiting such territorial behaviour (*pers. comm*, Private collector 1). Interestingly this private collector 1was the only keeper of *N. grayii* (of five keepers of this species) that reported such aggression. Another example reported a young *N. gemmeus* gecko biting another and a daughter seen several times edging itself over the mother below the heat lamp (professional keeper 4).

Table A.1.1. The results of this green gecko enclosure design survey conducted as part of this thesis. In total, seven responses were collected (with information on 16 green gecko enclosures): four from professional (n = 4) and 12 from private collectors (n = 3, all private collectors had >1 green gecko enclosure). Enclosure sizes and stocking densities used for previous green gecko penned translocations and some authorised holders throughout New Zealand based on responses to a green gecko enclosure design survey distributed in December, 2020. A release pen refers to an outdoor penned area within which geckos were temporarily confined for a defined period of time prior to release into the wider area. Studies reporting these pen areas have been added to the table to provide further information on the size and density green geckos have been held at. *Biting was observed once and a daughter seen several times edging itself over the mother below the heat lamp.

Enclosure Type	*Naultinus* species (no. enclosures)	Number of Individuals (and Life History Stage if known)	Adult sex-ratio (F:M)	Enclosure Area (m^3) and dimensions in m (length x width x height)	3D (and 2D) Space per Gecko (m^3, m^2)	Signs of stress or aggressive interactions?	References
Outdoor Enclosure (Kerikeri)	*N. grayii* (1)	1 adult 4 subadults (5 total)	3:1	0.40 (0.6 x 0.6 x 1.1)	0.10 (0.09)	No	Private collector 1
Outdoor Enclosure (Kerikeri)	*N. elegans* (1)	3 neonates	NA	0.30 (0.5 x 0.6 x 1)	0.10 (0.10)	No	Private collector 1
Outdoor Enclosure (Auckland)	*N. grayii* (1)	2 adults (cohabiting with 2 *Mokopirirakau granulatus*)	1:1	1.02 (0.8 x 0.8 x 1.6)	0.51 (0.32)	No	Professional keeper 1

Indoor tank (Auckland)	*N. elegans* (1)	8 adults (cohabiting with 4 *Oligosoma moco*)	1:7	2.34 (1.2 x 1.3 x 1.5)	0.29 (0.20)	No	Professional keeper 1
Outdoor Enclosure (Waihi)	*N. grayii* (1)	2 adults	1:1	1.09 (1.1 x 0.9 x 1.1)	0.54 (0.50)	No	Private collector 2
Outdoor Enclosure x 7 (Hamilton)	*N. elegans* (2) *N. gemmeus* (1) *N. grayii* (3) *N. stellatus* (1)	3-8 (most commonly 5)	~1:3 (3:2 *N. grayii*)	0.50 (1.2 x 0.6 x 0.7)	0.06 – 0.17 (0.09 – 0.24)	Aggressive territorial behaviour in some individuals	Private collector 3
Outdoor Enclosure (Hamilton)	*N. grayii* (1)	2 adults (cohabiting with 5 *W. maculata* and 1 *M. granulatus*)	1:1	2.90 (2.3 x 0.9 x 1.4)	1.45 (0.69)	No	Professional keeper 2
Indoor terrarium (Hawkes Bay)	*N. punctatus* (1)	1 adult	NA	0.24 (0.45 x 0.6 x 0.9)	0.24 (0.27)	No	Professional keeper 3
Outdoor Enclosure x 3 (Wellington)	*N. punctatus* (1) *N. elegans* (1) *N. grayii* (1)	3 adults 2 adults 5 adults	1:2 1:1 1:4	0.25 (0.5 x 0.5 x 1)	0.08 (0.08) 0.13 (0.13) 0.05 (0.05)	No	Private collector 4
Indoor Tank (Dunedin)	*N. gemmeus* (1)	3 adults	3:0	0.62 (1.5 x 0.5 x 0.82)	0.21 (0.25)	No*	Professional keeper 4

Indoor terrarium (Dunedin)	*N. gemmeus* (1)	1 adult	0:1	0.32 (0.8 x 0.45 x 0.9)	0.32 (0.36)	No	Professional keeper 5
Release Pen (3 months)	*N. punctatus*	19 adults	9:10	~100.00 m^2	5.26 m^2	NA	Flynn-Plummer and Monks, 2021
Release Pen (4 months)	*N. gemmeus*	11	NA	78.50 m^2	7.14 m^2	NA	Knox *et al.*, 2017
Release Pen (4 months)	*N. gemmeus*	5	NA	52.48 m^2	10.50 m^2	NA	Knox *et al.*, 2017
Release Pen (9 months)	*N. gemmeus*	24 adults 3 subadults 15 juveniles (42 total)	21:6	655.50 m^2	15.61 m^2	NA	Knox and Monks, 2014

Appendix 2: Article written for the Wildways column, ODT:

https://www.odt.co.nz/lifestyle/magazine/fantastic-geckos-and-where-find-them

Fantastic geckos and where to find them

Monday, 21 June 2021

A neonate (baby) jewelled gecko being released, December 2020. PHOTOS: SUPPLIED

Over the past summer, I was fortunate enough to search for the cryptic jewelled gecko within Orokonui Ecosanctuary for translocation to the ecosanctuary's new gecko enclosure, writes Ellen Richardson.

The main component of my research was comparing the movements and behaviour of the enclosure geckos to that of free-roaming jewelled geckos in the wider ecosanctuary, to ensure the enclosure is promoting natural behaviours.

There is a unique feeling of excitement when you are carefully walking through the bush, knowing that any second you could spot a jewelled gecko for the first time.

For me, by the fifth day of my fieldwork and a total of 14 hours searching without success for these elusive animals, the leaves and bushes were starting to blur together. I even resorted to pulling up photos on my phone to recalibrate my brain.

It turns out, searching for jewelled geckos in the hot summer heat of February isn't the best time to start training your eye. It was not until the following June when I had to contain my immense excitement and need to jump up and down - not only had I stumbled upon my first jewelled gecko, in a Coprosma shrub, but it was a perfect, miniature version - a baby jewelled gecko!

Jewelled geckos, known to scientists as Naultinus gemmeus, are one of New Zealand's nine species of green gecko (Maori: moko-kakariki).
Opportunities to view these strikingly coloured lizards, all of which are classified as either Nationally Vulnerable or At Risk and Declining, are limited, especially in naturalistic environments.

Poaching of green geckos has become a key

Striped pattern! This gecko is in the enclosure.

threat (in addition to predation by introduced mammalian predators and extensive habitat modification and removal of dense woody vegetation), and therefore a big concern for wildlife managers throughout New Zealand. The locations of wild green gecko populations are consequently not advertised to the public.

To enable a public opportunity to view our local species, in December 2020 Orokonui Ecosanctuary constructed a captive-breeding and viewing enclosure for jewelled geckos (in between the popular Otago skink and tuatara enclosures).

It is the first open-roofed, naturalistic, green gecko enclosure in New Zealand. The search for young individuals to translocate was not easy, but after six months and about 393 person-hours of effort from volunteers, Orokonui staff and me searching the wider ecosanctuary, the jewelled gecko enclosure welcomed its 10th and final housemate with open arms.

Now there are 10 geckos (juveniles, subadults and young adults) to try to spot in the enclosure. For the security of the geckos, the enclosure is bordered by a low fence with additional security measures in place.

Now that the enclosure is open for visits, you too can experience that overwhelming feeling of excitement and urge to fling arms up in the air.

Orokonui Ecosanctuary's new jewelled gecko enclosure.

But take some advice from me ... Walk carefully and quietly around and stare at those bushes. You're looking for even the tiniest variation in the shade of green; most of the time you'll realise it's just a gecko-shaped leaf, but practice makes perfect. The sunny bushes are where you want to focus your search. As ectothermic animals, jewelled geckos rely on basking in the sun to warm themselves up; the warmth helps speed up essential activities such as moving, eating and digesting food.

In the cooler months, the afternoon is the best time to spot the geckos basking. When it's cold, the geckos take longer to warm up and get the energy and motivation to expose themselves to the sun - much like us trying to get out of bed on those freezing winter mornings. In the warmer months, early morning is the time to search, before the geckos retreat into the bushes where they can remain warm without exposing themselves. These geckos are also arboreal, so they can be found at a range of heights. One gecko within the ecosanctuary was spotted about 5m up a manukatree. For viewing in the enclosure, bring binoculars if you have them, and make sure you search high and low. And finally, don't give up - spotting one of these tiny green geckos is well worth it.

- Ellen Richardson is researching the establishment of translocated jewelled geckos 9-11 years after their translocation into Orokonui Ecosanctuary and confirming the suitability of the sanctuary's jewelled gecko enclosure for her MSc in wildlife management in the Department of Zoology, University of Otago.

You may have spotted that this gecko doesn't have a full tail! This was a natural event that had occurred before the translocation. All of New Zealand's endemic lizards (geckos and skinks), are able to drop their tails to escape from predators

Appendix 3: Skin Abrasion and Sloughing Observed in Jewelled Geckos Following Transmitter Removal

Figure A.3.1. The 'backpack' harness design used to attach Holohil BD2N (0.43g) and BD2X (0.35g) transmitters and some responses in jewelled geckos. A, B: Attachment in two adult geckos. Transmitters weighed <3-7% of geckos' body weight and a hypoallergenic, self-adhesive fabric strip (approximately 22 cm x 3 mm) was used to secure transmitters. Strips were coloured green with a POSCA water-based, xylene-free pen for camouflage (the same design used in Knox and Monks, 2014). C, D: Skin abrasion (within circled areas) in two adult geckos after 19 (C) and 16 (D) days of attachment. Gecko C had already undergone a full shed after 10 days of transmitter attachment before a second transmitter was attached. E, F: Sloughing observed in two adult geckos following 16 (E) and 19 (F) days of transmitter attachment. Skin abrasion was not observed in one individual following 18 days of transmitter attachment.